Postharvest biology and technology of tropical and subtropical fruits

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Contents

Contributor contact details .... *xiii*
Woodhead Publishing Series in Food Science, Technology and Nutrition .... *xix*
Foreword .... *xxvii*

1 Cocona (*Solanum sessiliflorum* Dunal) **1**
O. Duarte, National Agrarian University, La Molina, Peru
1.1 Introduction 1
1.2 Fruit development and postharvest physiology 3
1.3 Maturity and quality components and indices 4
1.4 Preharvest factors affecting quality 4
1.5 Postharvest factors affecting quality 4
1.6 Physiological disorders 4
1.7 Pathological disorders 5
1.8 Insect pests and their control 5
1.9 Postharvest handling practices 6
1.10 Processing 6
1.11 Conclusions 6
1.12 References 6

2 Coconut (*Cocos nucifera* L.) **8**
J. Siriphanich, P. Saradhuldhat, T. Romphophak, K. Krisanapook, S. Pathaveerat and S. Tongchitpakdee, Kasetsart University, Kamphang Saen, Thailand
2.1 Introduction 8
2.2 Fruit biology and postharvest physiology 11
2.3 Quality components and maturity indices 12
2.4 Preharvest factors affecting quality 16
2.5 Postharvest handling factors affecting quality 17
2.6 Physiological disorders and pests 19

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2.7 Postharvest handling practices 20
2.8 Processing 26
2.9 Conclusions 29
2.10 Acknowledgements 30
2.11 References 30

3 Dabai (*Canarium odontophyllum* Miq.) **34**
P. Ding, University of Putra Malaysia, Malaysia
3.1 Introduction 34
3.2 Postharvest physiology 37
3.3 Harvesting 37
3.4 Maturity and quality components and indices 38
3.5 Postharvest handling factors affecting quality 38
3.6 Conclusions 39
3.7 References 39

4 Date (*Phoenix dactylifera* L.) **41**
E. M. Yahia, Autonomous University of Queretaro, Mexico and A. A. Kader, University of California, Davis, USA
4.1 Introduction 41
4.2 Fruit growth and development 45
4.3 Nutritional components and health benefits 50
4.4 Postharvest physiology 52
4.5 Maturity and quality indices 53
4.6 Preharvest factors affecting postharvest fruit quality 56
4.7 Postharvest handling factors affecting quality 57
4.8 Physiological disorders 57
4.9 Pathological disorders 59
4.10 Insect pests and their control 60
4.11 Postharvest handling practices 63
4.12 Processing 72
4.13 Food safety considerations 72
4.14 Conclusions 73
4.15 References 74

5 Durian (*Durio zibethinus* Merr.) **80**
J. Siriphanich, Kasetsart University, Kamphang Saen, Thailand
5.1 Introduction 80
5.2 Fruit development and postharvest physiology 82
5.3 Maturity and quality components and indices 86
5.4 Preharvest factors affecting fruit quality 93
5.5 Postharvest handling factors affecting quality 94
5.6 Physiological disorders 96
5.7 Pathological disorders 98
5.8 Insect pests and their control 99
5.9 Postharvest handling practices 100
5.10 Processing 106

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5.11 Conclusions 108
5.12 Acknowledgements 109
5.13 References 109

6 Feijoa (*Acca sellowiana* [Berg] Burret) **115**
W. C. Schotsmans, Institute of Agricultural Research and Technology, Spain, A. East, Massey University, New Zealand and G. Thorp and A. B. Woolf, The New Zealand Institute for Plant & Food Research Limited, New Zealand
6.1 Introduction 115
6.2 Preharvest factors affecting fruit quality 120
6.3 Postharvest physiology and quality 124
6.4 Postharvest handling factors affecting quality 125
6.5 Postharvest crop losses 127
6.6 Processing 129
6.7 Conclusions 130
6.8 References 131

7 Fig (*Ficus carica* L.) **134**
H. Crisosto, L. Ferguson and V. Bremer, University of California, Davis, USA, E. Stover, US Horticultural Research Laboratory, USA and G. Colelli, University of Foggia, Italy
7.1 Introduction 134
7.2 Fruit development and postharvest physiology 137
7.3 Maturity and quality components and indices 140
7.4 Preharvest factors affecting fruit quality 140
7.5 Postharvest handling factors affecting quality 145
7.6 Physiological disorders 147
7.7 Pathological disorders 147
7.8 Insect pests and their control 150
7.9 Postharvest handling practices 150
7.10 Processing 154
7.11 Conclusions 155
7.12 References 156

8 Golden apple (*Spondias dulcis* Forst. syn. *Spondias cytherea* Sonn.) **159**
M. Mohammed, University of the West Indies St Augustine Campus, Trinidad, S.Hajar Ahmad, R. Abu Bakar and T. Lee Abdullah, University of Putra Malaysia, Malaysia
8.1 Introduction 159
8.2 Fruit development and postharvest physiology 162
8.3 Maturity indices and quality components 165
8.4 Preharvest factors affecting fruit quality 166
8.5 Postharvest handling factors affecting quality 166
8.6 Physiological disorders 169

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8.7 Pathological disorders ... 171
8.8 Insect pests and control ... 172
8.9 Postharvest handling practices ... 173
8.10 Processing ... 175
8.11 Conclusions ... 176
8.12 References ... 177

9 Table grape (*Vitis vinifera* L.) ... **179**
J. P. Zoffoli and B. A. Latorre, Pontificia Universidad Católica de Chile, Chile
9.1 Introduction ... 179
9.2 Table grape cultivars ... 180
9.3 Fruit anatomy ... 181
9.4 Physiology of berry growth and maturation ... 182
9.5 Deterioration factors ... 184
9.6 Postharvest handling and packaging ... 192
9.7 Temperature management ... 196
9.8 Sulfur dioxide treatments ... 196
9.9 Quarantine treatments ... 201
9.10 Transport ... 202
9.11 Processing ... 204
9.12 Conclusions ... 207
9.13 References ... 207

10 Guava (*Psidium guajava* L.) ... **213**
S. P. Singh, Curtin University of Technology, Australia
10.1 Introduction ... 213
10.2 Fruit development and postharvest physiology ... 216
10.3 Maturity indices ... 219
10.4 Preharvest factors affecting fruit quality ... 220
10.5 Postharvest handling factors affecting fruit quality ... 222
10.6 Physiological disorders ... 227
10.7 Postharvest pathological disorders ... 228
10.8 Postharvest insect-pests and phytosanitary treatments ... 230
10.9 Postharvest handling practices ... 232
10.10 Processing ... 235
10.11 Conclusions ... 238
10.12 Acknowledgements ... 239
10.13 References ... 240

11 Jaboticaba (*Myrciaria cauliflora* (Mart.) O.Berg. [Myrtaceae]) ... **246**
G. H. de Almeida Teixeira, The University of São Paulo (USP), Brazil, M. F. Berlingieri Durigan, Embrapa Roraima, Brazil and J. F. Durigan, Universidade Estadual Paulista, Brazil
11.1 Introduction ... 246
11.2 Fruit development and postharvest physiology ... 254

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11.3 Maturity and quality components and indices ... 256
11.4 Preharvest factors affecting fruit quality ... 260
11.5 Postharvest handling factors affecting quality ... 261
11.6 Physiological disorders ... 264
11.7 Pathological disorders ... 264
11.8 Insect pests ... 265
11.9 Postharvest handling practices ... 266
11.10 Processing ... 268
11.11 Conclusions ... 270
11.12 References ... 271

12 Jackfruit (*Artocarpus heterophyllus* Lam.) ... 275
A. Saxena, A. S. Bawa and P. S. Raju, Defence Food Research Laboratory, Mysore, India
12.1 Introduction ... 275
12.2 Fruit growth, respiratory behaviour and ripening ... 279
12.3 Jackfruit composition and nutritional value ... 279
12.4 Preharvest factors affecting fruit quality and harvest timing ... 284
12.5 Postharvest handling practices ... 284
12.6 Pathological disorders and insect pests ... 288
12.7 Processing ... 288
12.8 Conclusions ... 295
12.9 References ... 295

13 Chinese jujube (*Ziziphus jujuba* Mill.) and Indian jujube (*Ziziphus mauritiana* Lam.) ... 299
J. P. Sheng and L. Shen, China Agricultural University, China
13.1 Introduction ... 299
13.2 Ripening behaviour and postharvest physiology ... 304
13.3 Postharvest pathology and entomology ... 307
13.4 Postharvest disorders ... 311
13.5 Preharvest treatments to extend shelf life ... 312
13.6 Postharvest treatments to extend shelf life ... 313
13.7 Postharvest handling ... 318
13.8 Processing ... 319
13.9 References ... 321

14 Kiwifruit (*Actinidia* spp.) ... 326
J. Burdon and N. Lallu, The New Zealand Institute for Plant & Food Research Ltd, New Zealand
14.1 Introduction ... 326
14.2 The *Actinidia* vine and fruit ... 327
14.3 Maturation ... 331
14.4 Postharvest physiology ... 333
14.5 Physiological disorders ... 341
14.6 Postharvest pathology ... 343

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14.7 Postharvest handling ... 346
14.8 Commercial practice ... 348
14.9 Future trends ... 353
14.10 Acknowledgements ... 353
14.11 References ... 353

15 Litchi (*Litchi chinensis* Sonn.) ... **361**
D. Sivakumar, Tshwane University of Technology, South Africa and L. Korsten, University of Pretoria, South Africa
15.1 Introduction ... 361
15.2 Fruit development, maturation and composition ... 363
15.3 Production of good quality litchi fruits for postharvest export chain ... 368
15.4 Constraints during long-term storage and export ... 370
15.5 Postharvest picking, in-field sorting and transport ... 379
15.6 Postharvest chain and packhouse treatments ... 381
15.7 Developments in postharvest technologies to replace sulphur dioxide fumigation ... 386
15.8 Processing ... 396
15.9 Conclusions ... 397
15.10 References ... 399

16 Longan (*Dimocarpus longan* Lour.) ... **408**
Y. Jiang, Chinese Academy of Sciences, China, D. Joyce, University of Queensland, Australia and H. Lin, Fujian Agriculture and Forestry University, China
16.1 Introduction ... 408
16.2 Postharvest characteristics ... 409
16.3 Postharvest handling ... 412
16.4 Packaging ... 415
16.5 Storage ... 416
16.6 Transport ... 417
16.7 Marketing ... 418
16.8 Processing ... 418
16.9 Conclusions ... 418
16.10 Acknowledgements ... 419
16.11 References ... 419

17 Loquat (*Eriobotrya japonica* L.) ... **424**
S. Tian, G. Qin and B. Li, Chinese Academy of Sciences, China
17.1 Introduction ... 424
17.2 Maturity and quality ... 426
17.3 Postharvest physiology ... 427
17.4 Physiological disorders ... 428
17.5 Postharvest diseases ... 431

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17.6 Postharvest treatments 432
17.7 Storage technologies 435
17.8 Conclusions 438
17.9 References 439

18 Lucuma (*Pouteria lucuma* (Ruiz and Pav.) Kuntze) 443
E. M. Yahia and F. Guttierrez-Orozco, Autonomous University of Queretaro, Mexico
18.1 Introduction 443
18.2 Fruit development and postharvest physiology 445
18.3 Maturity and quality components and indices 446
18.4 Postharvest handling factors affecting quality 446
18.5 Physiological disorders 446
18.6 Insect pests and their control 447
18.7 Postharvest handling practices 447
18.8 Processing 447
18.9 Conclusions 448
18.10 References 448

19 Macadamia (*Macadamia integrifolia, Macadamia tetraphylla* and hybrids) 450
H. M. Wallace and D. A. Walton, University of the Sunshine Coast, Australia
19.1 Introduction 450
19.2 Preharvest physiology 452
19.3 Quality components and indices 453
19.4 Preharvest factors affecting nut quality 458
19.5 Quality and the on-farm postharvest chain 460
19.6 Drying effects on quality 461
19.7 Handling and physical damage to macadamia 464
19.8 Factory processing of macadamia 464
19.9 Conclusions 468
19.10 References 469

20 Mamey apple (*Mammea americana* L.) 474
E. M. Yahia and F. Guttierrez-Orozco, Autonomous University of Queretaro, Mexico
20.1 Introduction 474
20.2 Fruit development and postharvest physiology 477
20.3 Maturity and quality components and indices 477
20.4 Postharvest handling factors affecting quality 478
20.5 Physiological disorders 478
20.6 Pathological disorders 478
20.7 Insect pests 478
20.8 Postharvest handling practices 478

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20.9 Processing 479
20.10 Conclusions 479
20.11 References 480

21 Mamey sapote (*Pouteria sapota* Jacq. H. E. Moore & Stearn) **482**
E. M. Yahia and F. Guttierrez-Orozco, Autonomous University of Queretaro, Mexico
21.1 Introduction 482
21.2 Postharvest physiology 484
21.3 Maturity and quality components and indices 485
21.4 Postharvest handling factors affecting quality 485
21.5 Physiological disorders 486
21.6 Pathological disorders 486
21.7 Insect pests and their control 487
21.8 Postharvest handling practices 487
21.9 Processing 488
21.10 Conclusions 489
21.11 References 489

22 Mango (*Mangifera indica* L.) **492**
E. M. Yahia, Autonomous University of Queretaro, Mexico
22.1 Introduction 492
22.2 Fruit development and postharvest physiology 501
22.3 Maturity and quality components and indices 509
22.4 Preharvest factors affecting fruit quality 512
22.5 Postharvest handling factors affecting quality 515
22.6 Physiological disorders 521
22.7 Pathological disorders and their control 524
22.8 Insect pests and their control 528
22.9 Postharvest handling practices 536
22.10 Processing 544
22.11 Conclusions 550
22.12 References 550

Index *567*

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Foreword

Not unlike the experiences of many of the readers of Professor Yahia's publications, my love affair with tropical and subtropical fruits began at a very early age. I was born and raised on our family farm near the southwestern shores of Lake Ontario in New York State, where we produced about 100 acres of various temperate fruits. However, for a unique Christmas treat we often enjoyed tropical and subtropical fruits, such as tangerines and bananas. During various stages in my career I have had the good fortune of working and living for nearly a dozen years in Latin American countries, where many of the delicious tropical fruits described in the four volumes of this postharvest reference were fairly common. Since then I have been pleased to observe some of these favorite fruit friends somewhat commercialized, thanks to favorable economics and the ingenuity of enterprising individuals.

Some of the tropical and subtropical fruit crops that most people only encounter during international travels may eventually find their way into commerce. Interestingly, as many of these tropical delicacies become better known, there is the tendency to explore export opportunities for more global consumption. Meanwhile, local populations enjoy the flavors and health benefits of the diverse array of tropical fruits that they have known most of their lives.

Banana is an example of a common household food that would perhaps still be a unique and exotic tropical fruit enjoyed mostly where it is produced were it not for the ingenuity and entrepreneurship of visionaries of the early twentieth century. Likewise, as Garrity points out in the Foreword of Akinnifesi *et al.* (2008), 'the domestication and commercialization of kiwi fruit is a classic case of a new fruit of international significance. New Zealand farmers began growing kiwi commercially in the 1930s despite its more than 1000 years' history in China.'

Each tropical fruit possesses unique characteristics expressed in appearance and flavor, and sometimes in its growth habit. These properties are often accompanied by nutritional benefits that make it attractive as a natural source of

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neutraceuticals. For uniqueness of growth habit, a personal favorite is jaboticaba. These beautiful black, smooth skinned, globose berries are borne on thick pedicels directly on the trunks and branches of the plant, rather than on stems like cherries, as one might expect. This lends a distinctive appearance to the fruiting tree, as illustrated by Almeida Teixeira *et al.* in their interesting chapter on jaboticaba. This is an example of one of those tropical fruits that most of us rarely, if ever, spot in the produce section of our favorite supermarket. On the other hand, keep your eyes open for small jars of tasty jaboticaba (or other tropical fruit) preserves, which I am fortunate to have in my refrigerator at home at the moment. This illustrates potential industrial applications of tropical and subtropical fruits, which may be exponentially increased when the tools to control quality after harvest are available in combination with entrepreneurial thinking and global markets.

A 2011 *Perspective* article of the Society of Chemical Industry (Kitinoja *et al.*) discusses the needs and challenges of developing good, science-based, simple methods for postharvest handling that can be made available in developing countries (many of which have become the global sources of tropical and subtropical fruits). A nagging reality that continues to prevail is that 'reducing rough handling is a simple yet neglected practice for reducing mechanical damage in fruits.' As a postharvest physiologist, I have felt for many years that postharvest education and training deserves a very high priority in our hierarchy of professional responsibilities. Postharvest research and its results, while continuing to be very important, are not being fully utilized and applied, resulting in the unacceptable rates of perishables losses that continue to be reported around the world. Among the conclusions and recommendations of Kitinoja *et al.* is that 'an integrated approach for postharvest science and education from grade school through trade school or university could reduce global food losses, by integrating postharvest information into the general agricultural curriculum in each county or state and their extension services, with much more emphasis on preventing losses, maintaining quality and nutritional value after harvest and ensuring food safety.' In other words, research on postharvest science and technology continues to be very important, but without careful handling, it is wasted.

Entrepreneurs engaged in the commercialization of tropical and subtropical fruits have prepared reference materials to facilitate sales and, in fact, educate traders. Illustrative of such references is the *re:fresh Directory*, published annually by the Fresh Produce Consortium (http://www.freshproduce.org.uk). It is interesting to note that *re:fresh Directory 2010* informs readers regarding 44 of the 70 fruits included in the four volumes of *Postharvest Biology and Technology of Tropical and Subtropical Fruits*. A beautiful, full color photograph illustrating each fruit accompanies information about worldwide sources of this commodity throughout the year. Also included is the botanical name, genus, species, family, and other English names or synonyms. Brief descriptive text for each fruit informs would-be buyers of some of the characteristics and uses of each product. For trade purposes, the price look-up number (PLU) for the more common fruits is also indicated.

Many volumes have been written over the years about tropical and subtropical fruits, as can been seen in both scientific and popular literature. Relatively few of

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these publications, however, have dealt with the information gap regarding the postharvest biology and technology of these fruits. Contributors to *Indigenous Fruit Trees in the Tropics* (Akinnifesi *et al.*, 2008) remind us that 'indigenous fruit and nut trees of the tropics, have been described as "Cinderella species" because they have been overlooked by science and development.' Although many of these fruits are relatively obscure, they in fact, 'represent a unique asset that could be developed, domesticated and owned by farmers.' Many of the species discussed by Akinnifesi *et al.* are the same as those in Professor Yahia's *Postharvest Biology and Technology of Tropical and Subtropical Fruits* volumes.

A significant difference between references such as Akinnifesi *et al.* and that of Professor Yahia *et al.* is the essential and timely focus of these four excellent volumes on the importance of postharvest biology and technology issues. Such emphasis will pay dividends by educating readers, enhancing the use(s) of tropical and subtropical fruits, and contribute to the diversity of diets of consumers around the world.

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1

Cocona (*Solanum sessiliflorum* Dunal)

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Abstract: Cocona (*Solanum sessiliflorum*) is a tropical species which originated on the eastern slopes of the Andes of Peru, Colombia, Ecuador and Venezuela and the Amazonian part of Brazil. It is cultivated between 200 and 1000 m altitude. It is a semi perennial herb that turns semi woody with age and can reach 2 m in height. The round, oval or ovoid fruits are climacteric and are consumed raw or used to prepare juices, jams, jellies, hot sauces and pickles, and are also used in popular medicine. The fruits are hard and can withstand quite rough handling after harvest. It is important only locally but it could become more widely known since it has some desirable characteristics. Commercially it is better grown as an annual crop in order to maximize yields.

Key words: *Solanum sessiliflorum*, cocona, climacteric, popular medicine, fruit juices, chilling injury.

1.1 Introduction

1.1.1 Origin, botany, morphology and structure

Cocona (*Solanum sessiliflorum*) is native to the eastern slopes of the Andes of Peru, Ecuador, Colombia and Venezuela as well as the Amazonian part of Brazil. It belongs to the Solanaceae and the genus *Solanum*. At present it is named *Solanum sessiliflorum* but was previously known as *Solanum topiro* and earlier as *Solanum hyporrhodium*. In Spanish it is called *cocona*, *topiro* or *tupira*; in Brazil it is called *cubiú* and in English it is sometimes called peach tomato.

Cocona is a herbaceous semi perennial plant that can become partially woody with age, has a branching habit and can reach 2 m in height and live up to 3–5 years. In open spaces it tends to stay shorter and if there are adverse soil conditions it will become infested with root diseases very soon and will live for about one year. (See Plate I in the colour section between pages 274 and 275.) For commercial purposes it is recommended to produce it with

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higher densities as an annual crop. The roots are fairly well ramified with a main pivotal root in seed propagated plants, and root depth is around 50–60 cm (Duarte, 1997).

The leaves are very large, around 30–60 cm in length and 25–35 cm in width. They are simple, entire and alternate, covered with whitish hairs on both sides, with the upper side having more rigid hairs (Plate I). The petioles are about 15 cm long. The central and lateral leaf nerves are very prominent and yellowish-white in color. The leaf base is asymmetrical with acuminated lobules. Leaf margins are lobated, dented and sinuous (Donadio *et al.*, 2002).

The flowers have a star-like form when open with a diameter of about 4–5 cm and come in axillary inflorescences of 5 to 15 flowers each, with a peduncle about 0.3 to 0.5 cm long (Donadio *et al.*, 2002). The flower has five petals that are creamy with a yellow tint at their base. The five sepals are stiff and green in color and normally remain attached to the harvested fruit. Flowering starts about six months after transplant. The flowers open sequentially and if temperatures are adequate flowering will be almost continuous. The plant is allogamous and it is estimated that one plant can produce around 1000 flowers in a year of which about 5% will set fruit.

The fruit is a berry that can be oval, ovoid or round shaped. It starts out a dark green colour and ripens with a yellow-orange colour (see Plate II in the colour section between pages 274 and 275) that can become reddish orange in very ripe fruits. Fruit weight can go from 30 to 400 g and with a width of 5 to 8 cm and a length of 5 to 12 cm. They have 4 to 6 locules filled with soft creamy yellowish coloured pulp where numerous small cream coloured seeds are embedded (Plate II). The pulp is juicy, fragrant, not very sweet but with a characteristic taste and aroma and slightly acid (Gallozzi and Duarte, 2007). The soft pulp can be scooped out and a 'hoof' of hard pulp or pericarp will remain. This is insipid in flavor but can be eaten. The fruit peel is soft, 1 to 3 mm thick and has a bitter taste. The fruits are pubescent, with soft hairs that can cause allergic reactions in some people. Therefore it is recommended to harvest the fruits early in the morning, before the hairs dry out, so that they do not get loose in the air and enter into contact with the nose, eyes or skin of the laborers. The more ripe the fruit the less hairy it will be. These hairs are normally removed by rubbing with the hands or a cloth before taking the fruits to the market. The fruit is harvested by twisting it or cutting the peduncle. The sepals will remain attached to it.

1.1.2 Worldwide importance and economic value

Cocona is not important worldwide. There is a certain amount of consumption around the production areas and in a few cases small amounts will reach large city markets, but in general it is not a very well known fruit although it has some potential. It is basically consumed in the local markets in its areas of origin or by small producers.

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1.1.3 Culinary uses, nutritional value and health benefits

Cocona is a fairly nutritious fruit (Table 1.1). Juice can be made from it by scooping out the soft pulp (Plate II) and mixing it with water and some sugar in a blender, after which the seeds can be separated in a strainer. Sometimes the hard pericarp is boiled after peeling and also used to make juice, but its flavor is not as good as that of the soft inner pulp. The soft inner pulp can also be used to make hot sauce by mixing it with hot chilli pepper, salt and spices to enhance the flavor of meat, poultry and even fish. Jams can also be prepared with the hard pericarp after peeling (Duarte, 2004). Some people eat the raw fruit by cutting it into slices. In Brazil the leaves are sometimes boiled and eaten. In folk medicine the fruit is used to lower uric acid, glucose and cholesterol levels (Donadio *et al.*, 2002). It is also utilized by the indigenous people of eastern Peru to rid the head of lice (Morton, 1987).

Table 1.1 Composition of cocona fruits per 100 g of fresh edible portion (Gallozzi and Duarte, 2007)

Water	82–88.5 g
Ether extract	1.4 g
Raw protein	0.6–0.9 g
Fiber	0.4–9.2 g
Carbohydrates	5.7–9.2 g
Ashes	0.7 g
Calcium	16.0 mg
Phosphorus	30.0 mg
Iron	1.5 mg
Carotene	0.18 mg
Thiamine	0.06 mg
Niacin	2.25 mg
Ascorbic acid	4.50 mg
Energetic value	41 Kcals

1.2 Fruit development and postharvest physiology

There is no published information on postharvest physiology. The cocona is a climacteric fruit like its relative the tomato, since it can be harvested when its colour is still half green and it will complete ripening after harvest, becoming completely coloured and acquiring a slightly improved flavor (Plate II). This flavor is probably not as good as that of a fruit harvested when completely yellow or orange in colour.

1.2.1 Fruit growth, development and maturation

Fruit development will take about 60 to 80 days from anthesis to ripening according to climate. The fruit starts with a very dark green colour that becomes paler when

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ripening time is close. As it becomes riper it turns to yellow, then orange yellow and finally can reach a reddish orange colour when completely ripe or overripe. The fruit starts with a very dense pubescence that becomes less dense as it ripens.

1.2.2 Respiration, ethylene production and ripening

There is no written information on this aspect but the fruit is definitively climacteric.

1.3 Maturity and quality components and indices

No maturity standards or indices have been developed for this fruit. The main criterion used for maturity is fruit colour: the darker and more uniform the color the better. As for quality, size and shape of the fruit are important aspects. Freedom from mechanical damage as well as from insect or fungal attacks can be another factor. Sometimes people will consider colour as a purchase criterion, depending on how the fruit will be used or how long it will have to be stored before use.

1.4 Preharvest factors affecting quality

Some diseases and pests that damage the fruit or the peel will affect quality. Lack of proper fertilization or irrigation can also have an effect in diminishing fruit size. Defoliation can cause severe sunburn of certain fruits that will eventually result in rotting after harvest or even discarding the fruit if burn is severe. There in no written information on this aspect.

1.5 Postharvest factors affecting quality

If the fruit has been handled roughly during and after harvest, as well as exposure to the sun after harvest can have a detrimental effect. Storage conditions, especially temperature and relative humidity, will obviously play an important role. Color at harvest time will have a certain influence since fruits harvested completely colored will have a better taste compared to those harvested in the green-yellow stage, although they will have a shorter shelf life compared to fruits harvested half coloured as with most climacteric fruits where harvesting at an earlier stage prolongs the postharvest life.

1.6 Physiological disorders

At storage temperatures below 12–13°C, like most tropical fruits, the cocona fruit will show chilling injury after it is transferred to room temperature, and it

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deteriorates quickly. Very little experimental data about this species exist, especially in this area.

1.7 Pathological disorders

Like most species of the Solanaceae family, cocona is very susceptible to root rots caused by fungi like *Phytophthora*, *Rhizoctonia* and *Pythium*. They normally attack the root system and eventually the plants will die. To control this problem, crop rotation is recommended. In other words, a crop should not be cultivated immediately in the same field where a species of this family has been grown. Normally a different crop that is not a host to these fungi should be grown in order to eliminate or reduce the fungal presence. It is also important to avoid too heavy or too wet soils that favor these fungi. Another practice is to irrigate very carefully and to prevent water from staying too long around the base of the stems. Good drainage would be another important aspect in places where the land has a tendency to flood. Another fungal disease caused by *Sclerotium* sp. has also been associated with wilting.

The leaves can be infected by *Phytophthora infestans* and also by the fungus *Septoria solanicola*, and both can be controlled with copper based fungicides. Fruits and leaves can be attacked by the fungus *Colletotrichum gloeosporioides* that causes anthracnosis. This disease causes rotting of the attacked surface which in case of the fruit shows as black spots that give the fruit a poor look. This fungus can be controlled with 'Penconazol' or 'Mancozeb'.

Bacterial wilt caused by *Pseudomonas solanacearum* can be another problem. These rots are detected because the infected parts of the plant smell very bad and the damaged area is normally moist. Copper fungicides, especially copper hydroxide, can help in their control.

1.8 Insect pests and their control

Young plants are attacked by *Diabrotica*, an insect that if not controlled can eliminate 80% of the leaf area, although at later stages it is not as important.

The fruit can be attacked by *Planococcus pacificus* Cox (ripe fruit mealy bug), and *Phyrdenus muriceus* Germar, a yellow insect that causes black necrosis. There is also a fruit worm called *Neoleucenoides elegantalis* that can be controlled with *Bacillus thuringiensis* based insecticides. Another insect is *Faustinus apicalis* which can be controlled with products like Diazinon.

There are also *Thrips* that can be controlled with chlorpyripho*s* and aphids (*Myzus persicae*) that damage the leaves and can be controlled with *Verticillium lecanii*. Cocona is also prone to attack by rootknot nematodes (*Meloidogyne* sp.) as well as to the reniform nematode (*Rothylenchulus reniformis*) and *Helicotylenchus*. The best solution is to use resistant types and the significant addition of organic matter to the soil.

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1.9 Postharvest handling practices

Cocona fruits are hardy and have a thick peel as well as a solid pericarp or 'hoof', and therefore they can withstand rough handling compared to most other fruits, in a similar way to industrial tomatoes. The fruit can be maintained in good condition for at least a week in room conditions (27–30°C). In a household refrigerator they can be kept with no problems for almost a month without losing their flavor, but after being transferred to room temperature they will show chilling injury. For commercial storage, after preliminary trials a temperature of 15°C and 80–90% relative humidity are recommended and the fruit will remain in good condition for about three weeks after which it will start shriveling, losing firmness and showing an accelerated loss of weight. The use of coatings like the ones derived from sucrose or specially formulated waxes to be used on fruits will improve shelf life significantly and make the fruit look more attractive.

1.10 Processing

Cocona is not processed industrially on a large scale. Most of the processing is at household level or as cottage industries, for domestic consumption. Processing studies have shown that 10 kg of fruit will yield about 3 liters of preserved soft pulp and 1.5 liters of jelly or 7.5 liters of juice. A plantation producing 70 tons ha^{-1} will yield about 20 000 liters of preserved flesh, 10 000 liters of jelly, or 50 000 liters of juice.

1.11 Conclusions

This relatively unknown fruit merits wider distribution on a small scale in the tropics since it has many virtues from the nutritional standpoint. It is also a fairly tough fruit that will tolerate rough handling better than most fruits and has industrial potential. Besides this, being a semi perennial it quickly starts producing returns for the grower. The main problem when growing fruit trees is that it can take many years before income exceeds the break even point and the set-up costs, and the initial debts are paid. So this species could be used as an associated crop in tree orchards to help farmers to get early returns. More research needs to be done on this fruit.

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Plate I (Chapter 1) Cocona plants grown as an annual crop showing immature and almost mature fruits as well as plant and leaf size under this system. Notice the hairy young fruits.

Plate II (Chapter 1) Cocona fruit. Notice the greenish color of ripening fruit and the soft pulp in the inside that contains the seeds. Fruits have been wiped to remove hairs.

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2

Coconut (*Cocos nucifera* L.)

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Abstract: Coconut is a wonder fruit which provides the consumer with both a refreshing drink from its water and energy from its kernel. The oil from the mature kernel is used as cooking oil and processed into soap and detergent. The tree itself is known as 'the tree of life', since it also provides the locals with shelter and numerous products besides food. The dry kernel or copra was once an important international commodity. After World War II, its importance diminished partly due to the false opinion that coconut oil is an unhealthy food containing high amounts of saturated fat. The result was lower demand and depressed prices. Recently, demand for coconut is reviving, especially for its virgin oil as well as for young fresh fruit, both now recognized as healthy food. This chapter provides insight into postharvest biology and technology of the fruit involving both its water and kernel at both young and mature stages. Hence readers are advised to distinguish between these two parts and stages of the fruit.

Key words: *Cocos nucifera* L., coconut, postharvest biology, postharvest technology, postharvest processing.

2.1 Introduction

2.1.1 Botany, morphology and structure

Coconut, *Cocos nucifera* L., is the only species in *Cocos* genus, within *Aracaceae* family, *Cocoeae* order. The chromosome number is of 2n = 32 (Teulat *et al.*, 2000). Generally coconut is classified into dwarf and tall groups. Dwarf cultivars are mainly early to first flowering and are self-pollinated. Pollen shedding overlaps with the opening of the female flowers. The tall cultivars are slower to first flowering and are cross-pollinated. Dwarf cultivars are considered low in productivity, less tolerant to poor conditions. They have smaller kernels but produce more bunches per year,

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and are more resistant to lethal yellowing disease caused by a phytoplasma as compared to the tall cultivars (Ohler, 1984; de Taffin, 1998). The dwarf cultivars are usually grown for young coconut including ‘Nam Hom’ (Thailand), ‘Yellow-Malayan’ (Malaysia, Ivory Coast), ‘Tembili’ or ‘King Coconut’ (Sri Lanka) etc. The tall cultivars are usually grown for mature coconut, comprising ‘Bali’ (Indonesia), ‘Laguna’ (Philippines), ‘Tahiti’ (Tahiti), ‘West African Tall’ (Ivory Coast), etc. Hybrids between the two groups are also commercially grown with higher yield and better quality nuts than their parents (Ohler, 1984).

Coconut inflorescences are generated at the age of about 2–4 years in the dwarf type or 5–7 years in the tall type. In a year a coconut tree generally produces 12–20 inflorescences. The immature inflorescence (spadix) is covered in spathes. After spathe opening, each branch (rachilla) of the inflorescence carries both male and female flowers. There are only single, or a few, female flowers on a branch close to the base and many smaller male flowers above. Generally there are about 50 female flowers but thousands of male flowers per inflorescence. Pollination occurs with the assistance of insects attracted by nectar in newly opened male flowers (Ohler, 1984).

The fruit of the coconut is a fibrous drupe. Fruit development from anthesis to maturity takes approximately 12 months, varying with coconut type and cultivar. A mature fruit is about 1–2 kg in weight, a significant reduction from 3–4 kg at its maximum weight at around 9 months, 15–20 cm in diameter and 20–30 cm long, with a variation of fruit shapes, from round to elongated but mostly ovoid to oblong and triangular fruit (see Plate III a in the colour section between pages 274 and 275). Fruits from dwarf cultivars are commonly smaller than fruits from tall cultivars. The exocarp, or the epidermis, is about 0.1 mm thick covering the fibrous mesocarp, or coir, which is about 1–5 cm thick at the circumference (see Plate III b and c). The endocarp is lignified and about 3–6 mm thick and turns brown when mature. There are three eyes (see Plate III d), one on each carpel at the stem end. Two of the eyes are lignified. The other is a soft eye having the embryo located underneath. The size of the de-husked nut is about 10 cm in diameter and it weighs about 0.5 kg on average (Child, 1974; Grimwood, 1975; Ohler, 1984).

Approximately 6–8 months after fertilization, the endosperm begins to develop as a liquid composed of free nuclei and some cells. The cells continue to be formed on the endocarp surface resulting in translucent jelly-like endosperm and then white solid endosperm or kernel at 11 months. The tiny embryo is about the size of a pea seed under the soft eye (Cutter *et al.*, 1952; Child, 1974; Janick and Paull, 2008). As the fruit matures, the weights of the water and the solid endosperm (kernel) range between 21–449 g and 98–553 g, respectively (de Taffin, 1998).

2.1.2 Origin, distribution, production area and trade value

Coconut trees are found throughout the tropical areas of the world. However, the large diversity of coconut types found in Southeast Asia and Melanesia indicates that this region is the center of origin (Ohler, 1984).

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Table 2.1 Average annual coconut harvested area, production and yield among the top five producing countries during the past five decades, from 1961 to 2008

	Country	1961–68	1969–78	1979–88	1989–98	1999–2008
Area harvested	Indonesia	1096	1446	1952	2426	2717
(1000Ha)	Philippines	1527	2265	3218	3179	3333
	India	856	1074	1198	1670	1893
	Brazil	196	182	166	227	276
	Sri Lanka	462	457	423	432	420
Production	Indonesia	5571	7074	9455	13 224	16 846
(1000 tons)	Philippines	6541	8256	8942	11 008	14 097
	India	3748	4359	4831	8587	9239
	Brazil	372	362	356	740	2657
	Sri Lanka	1992	1791	1783	1880	2075
Yield	Indonesia	5.1	4.9	4.8	5.5	6.2
(Tons/Ha)	Philippines	4.3	3.6	2.8	3.5	4.3
	India	4.4	4.1	4.0	5.1	4.9
	Brazil	1.9	2.0	2.1	3.2	9.6
	Sri Lanka	4.3	3.9	4.2	4.4	5.0

Because it needs a warm climate, coconut can grow well only in tropical areas with a favorable temperature of 27°C ± 7°C. Coconut trees in cooler areas grow more slowly than those in warmer regions. In the equatorial areas, the plants grow well up to 600 m above sea level. At temperatures below 15°C, plants can survive but inflorescence abortion occurs. Although coconut trees grow on a wide range of soil types, the preferred soil is river alluvial deposits with good drainage. Evenly distributed rainfall is also preferred (de Taffin, 1998; Ohler, 1984).

At present, a large number of coconut orchards are held by small farmers in tropical developing countries. The production and trade value have increased slightly in the last few years. In 2008, global production was nearly 61 million tons. About 85% is from Asian countries, 8% from American continental countries. The top five producing and exporting countries are shown in Tables 2.1 and 2.2. Commercially the global harvested area in 2008 was 11.2 million ha of which 84% was located in Asia. However, the highest yield is obtained in Peru at 13.5 ton/ha. Global copra oil production was about 3.7 million tons in 2007–2008. Copra production from the Philippines, Indonesia and India was about 41, 25 and 12% of global production, respectively. Major importing countries (Table 2.2) are the US and China (FAO, 2010). For young coconut, Thailand is the main exporter to the US, Taiwan and Hong Kong with a value over 11 million USD in 2006 (Tangtermthong, 2008). The trend is increasing.

2.1.3 Use: fresh, processed products and nutritional value

Coconut plants are of great usefulness in providing food, fiber and wood and are described as the 'tree of life' (Ohler, 1984). The fresh fruit can be used at both immature (green) and mature stages. The young green fruit are used for coconut water (liquid endosperm) which is a refreshing drink with plenty of sugar and

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Table 2.2 Average annual export and import statistics of coconut fruit among the top five exporting and importing countries during the past five decades, from 1961 to 2007

Export	Country	1961–67	1968–77	1978–87	1988–97	1998–2007
Quantity *(tonnes)*	US	11906	15665	18869	13102	25237
	China	3294	6513	75113	23677	79755
	Netherlands	520	1727	5227	8450	11099
	UK	3907	4051	4390	5104	5534
	Singapore	2179	2818	21236	34917	13399
	Germany	2420	2804	3320	4760	3662
Value *(1000 $)*	US	634	1675	4128	5349	11672
	China	598	1679	9143	8744	7878
	Netherlands	115	441	2020	3369	4102
	UK	497	790	1721	2220	3422
	Singapore	64	129	2108	3824	3225
	Germany	328	745	1537	3550	3289

potassium, vitamins B and C and tender flesh (solid endosperm). Coconut water is also widely used in the culture of plant tissues due to the presence of plant growth hormones, particularly auxin and cytokinin that stimulate cell division and growth (Tangtermthong, 2008; Yong *et al.*, 2009).

The fresh kernel in mature fruit contains 35–64% water, 25–44% oil, 9–14% carbohydrate and 5 mg/100 g vitamin C (Child, 1974; Grimwood, 1975; Ohler, 1984). Its dried kernel, or copra, was an international raw material for vegetable oil, soap, detergent and margarine from the mid-nineteenth century to the 1960s. The oil itself consists mostly of saturated fatty acid and is fairly stable at ambient conditions, lasting over two years. At present the virgin coconut oil, prepared by a cold-pressed process directly from the fresh kernel and retaining coconut scent, is used mainly as a health product. The outer husk (mesocarp) fiber from dry fruits is versatile, used for mats, ropes, textiles, and non-fiber products. The residual coir dust, or cocopeat, is used as a plant growing medium when completely or partially decomposed. Coconut milk is made by shredding and squeezing the kernel from mature fruit, and is used in Asian dishes and desserts (Foale, 2003; Woodroof, 1970).

2.2 Fruit biology and postharvest physiology

2.2.1 Fruit growth, development and maturation

The coconut development time from anthesis to full maturity is about 11 to 13 months, shorter in the dwarf cultivars. The exocarp is waxy and green, yellow, ivory or red-brown in colour, before turning to brown or gray at full maturity. The mesocarp or husk is fibrous, while the endocarp or the shell is woody, hard and dark brown in colour (Child, 1974).

The fruit reach the maximum size at around 5–6 months. During the first 6 months only the husk and shell develop quickly and the cavity is full of water. In the following 6–8 months the husk and the shell harden and thicken and turn

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dark brown. At the same time the kernel or solid endosperm starts to form, appearing as jelly-like material beginning at the stylar end at 6 months, and develops towards the stem end. As it develops it becomes thicker and turns white, and it is fully formed at 10 months having 10–15 mm in thickness. Around the solid endosperm is the reddish brown testa, or seed coat, which lies firmly underneath the shell (Child, 1974; de Taffin, 1998).

The liquid endosperm in the cavity starts to disappear near fruit maturation, resulting in a sloshing sound when the fruit is shaken. What portion of the water has evaporated or been absorbed into the solid endosperm is not clear. At full maturity the husk portion is about 31–54% by weight, the shell 12–16%, the kernel 28–33% and the water 6–25%. Based on dry weight the husk reaches its maximum growth at 8 months, the shell at 12, the kernel at 11 and the oil at 13 months (Child, 1974; Grimwood, 1975; de Taffin, 1998).

During the maturation process, the sugar content in the liquid endosperm increases from about 1% during the first few months after anthesis to a maximum of 5–8% by the sixth to eighth month, then declines to about 2% at full maturity in the tall cultivars (Child and Nathanael, 1950). In the early stages sugars are in the form of glucose and fructose. Sucrose appears later in small amounts and after six months sucrose content increases to 1–2% at full maturity, while the reducing sugars fall to 1% (Child and Nathanael, 1950; Jayalekshmy *et al.*, 1986). The oil content in the solid endosperm increases from a trace during the first three months to 35–40% fresh weight at full maturity (Ohler, 1984).

2.2.2 Respiration and ethylene production

De-husked mature coconuts respire at about 50 mg $CO_2 kg^{-1} hr^{-1}$ at 25°C (Paull and Ketsa, 2004). Whole young coconuts of six months after anthesis respire at about 30 mg$CO_2 kg^{-1} hr^{-1}$ at 25°C soon after harvest and this declines gradually during storage. Ethylene production is about 0.24 $\mu l C_2H_4 kg^{-1} hr^{-1}$ and increases continuously after seven days in storage (Romphophak and Thongbor, 2008). Trimmed young coconuts produce more ethylene and respire at higher rates (Meethaworn and Siriphanich, 2009).

2.2.3 Ripening behavior

At full maturity, around 11–13 months after anthesis, the peel tissue senesces, and the color changes from green or other colors to gray. The husk becomes dry. No other change can be observed. Hence, we consider that coconuts mature without any ripening behavior.

2.3 Quality components and maturity indices

2.3.1 Fruit shape, kernel and liquid content

Coconuts with an oblong shape usually have small nuts and have low kernel and liquid content. The thickness of the kernel is the most important criterion for the

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mature coconut. Thick kernels yield more copra and hence more oil can be extracted. The shell should be strong enough to prevent the nut cracking during transport but not too thick or hard to prevent it being split open. The amount of liquid inside, as can be detected by the sloshing sound when shaken, indicates the maturity as well as the freshness of the nut. The fruit that is light with less water inside may have been harvested for a long time and the liquid endosperm have evaporated or been absorbed by the endosperm. The color of the husk on the fruit should be brown, not gray, which indicates an old nut. The soft eye should be dry and brown without any discoloration and with no embryo protruding. Otherwise, the invasion of microbes into the kernel inside is likely. The nut should be free of patchy staining due to a crack in the shell allowing leakage of water from the inside (Foale, 2003).

2.3.2 Moisture, sugar, acid and oil content

Young coconut

Soluble solids contents in the water of a young coconut are about 5% at around 6–7 months after anthesis. The 'NamWan' (sweet water) cultivar in Thailand contain 6.5–7.0% soluble solids. Sri Lanka's 'King Coconut', grown only for drinking, has an even higher soluble solid content (Janick and Paull, 2008). In other dwarf hybrids, the contents were found to total up to 9% (Petchpiroon, 2006). In the 'NamHom' (aromatic water) cultivar, glucose is the main sugar of coconut water (2%), followed by fructose (1.2%) and sucrose (0.6%). On the other hand, the solid endosperm contains about 1.4% sucrose, 0.8% glucose and 0.55% fructose (Romphophak and Thongbor, 2008).

Jayalekshmy *et al.* (1986) reported an increase in titratable acidity in an Indian fruit during its development to a maximum of about 0.14% before it decreased to about 0.06% at full maturity. However, Jackson *et al.* (2004) reported a range of 0.06–0.08% in dwarves. The pH of the water was recorded to be between 4.6 and 6.7 (Jackson *et al.*, 2004; Wijeratnam *et al.*, 2006).

Fat content in young coconut water was reported to be from 0.01–1.8%, with similar composition as in mature coconut water (Campos *et al.*, 1996; Jayalekshmy *et al.*, 1986; Jackson *et al.*, 2004). In the kernel, fat content is around 1–4% fresh weight (Grimwood 1975; Gatchalian *et al.*, 1994). During storage, fat content increases (Gatchalian *et al.*, 1993). However, our study shows that saturated fatty acids decrease while unsaturated fatty acids increase. Starch is also found between 0.4–3.5% of fresh weight in the young coconut kernel. The content increases during storage (Gatchalian *et al.*, 1993). Another polysaccharide found in the kernel is mainly polygalactomannan (Balasubramaniam, 1976). The moisture content of the kernel ranges between 66–87%, depending on the fruit maturity (Gatchalian *et al.*, 1994; Romphophak and Thongbor, 2008).

Mature coconut

Moisture content of the fresh kernel was nearly 90% at around 8 months, which decreased to 50–60% at maturity. Oil in the coconut kernel is mostly (91%)

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saturated fats of C-6 to C-22 fatty acids, with mostly the short and medium chain fatty acids. The C-12 lauric acid accounts for nearly 50%. The fat content at harvest is around 36–41% fresh weight. After drying, to about 6% moisture, the fat content increases to 60–74%. Free fatty acid content decreases from around 6% at 7 months to 0.5% at full maturity (Child, 1974; Ohler, 1984).

In the water of the mature coconut, sugar content is about 2–3%. Higher sugar content up to 4.3% was also reported but may have been from desiccated samples (Grimwood, 1975). It might contain equal amounts of reducing and non-reducing sugars or mainly reducing sugar or non-reducing sugar depending on the cultivars (Child and Nathanael, 1950; Grimwood, 1975; Jackson *et al.*, 2004). Sorbitol was reported at around 1% (Grimwood, 1975). Titratable acidity ranges from 0.06 to 0.1%. The pH was recorded as rather acidic of pH 3.1–3.5 and gradually increased to about 6 at maturity (Ohler, 1984). Fat content is from 0.8–1.8%. Fat content of about 0.8% was reported in the Indian West Coast Tall cultivar. The main fatty acids are C-8:0, 10:0, 12:0, 14:0, 16:0 and 18:1 covering about 9, 5, 47, 19, 7 and 4% of total fat, respectively (Jayalekshmy *et al.*, 1986).

The saturated fats in coconut were once labeled and widely publicized as bad fat. It was later shown that was not the case, as testified to the US Senate on tropical oil by Harvard Medical School on December 1, 1987: 'It is now apparent that selective labeling requirements that focus on the lauric acid tropical oils (coconut and palm kernel) would represent an inaccurate and misleading use of existing data. There is simply no scientific basis for describing coconut oil as a health risk.' 'Saturated fats (of coconut) composed principally of medium chain triglycerides do not elevate serum cholesterol when taken as part of the normal diet. The chemical properties of medium chain triglycerides are such that they are rapidly metabolized, and therefore contribute a preferred energy source for the body. As a result, unlike other saturated fats, they are not stored in the body as fat' (Persley, 1992). Unfortunately this information has not been well publicized.

2.3.3 Other components

Mature coconut water contains many vitamins but in small quantities. Ascorbic acid is the main one ranging 0.7–5 mg/100 g (Grimwood, 1975; Janick and Paull, 2008). Wijeratnam *et al.* (2006) reported a range of 1.5–3 mg/L ascorbic acid in young coconut water. The young kernel has up to 7 mg/100 g acerbic acid content. Antioxidant capacity of compounds found in coconut water was reported in two Brazilian coconut cultivars (da Fonseca *et al.*, 2009).

Among volatiles, delta-C8, -C10 lactones and n-octanol were the major volatiles responsible for the mature coconut flavor (Lin and Wilkens, 1970), while pyrazines are responsible for the roasted taste of roasted coconut (Jayalekshmy *et al.*, 1991). For the aromatic young coconut 2-acetyl-1-pyrroline, the same compound found in Thai jasmine rice, was identified along with many other volatiles (Auttarint, 2005).

There are no standards for mature coconut. In Thailand a standard for young coconut was approved in 2007. The fruits are classified into three classes: extra, class I and class II according to the difference in the degree of defect. The extra

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class allows only very slight superficial defect, while classes I and II allow up to 5 and 10% of total surface area. The weight of the trimmed coconut should be in the range of 700–1400 g per fruit, while the polished coconut had three size classes, i.e. 350–450, >450–600 and >600–850 g (National Bureau of Agricultural Commodity and Food Standard, 2007).

2.3.4 Maturity indices

Young coconut

The most common maturity index used for young coconut is the duration after a certain point of flower development, varying between cultivars, growing locations and the season. In Thailand farmers use the term 'number of pulp layer' for their comparisons. One layer fruit refers to the stage about 6 months after anthesis during which the solid endosperm has just formed on the inner surface of the shell and it is still translucent. The one-and-a-half layer refers to fruit about 6.5 months after anthesis having white endosperm on the stylar end, while that on the stem end remains translucent. The two-layer number refers to fruit about 7 months after anthesis with most of the endosperm white except around the area underneath the soft eye at the stem end of the fruit (Plate IIIb). The two-and-a-half layer fruit, 7.5 months after anthesis, refers to the fruit that has all parts of the solid endosperm already white. The suitable stages for export are the one-and-a-half and two-layer coconuts. The two-layer coconuts can be stored for as long as two months, while the one-and-a-half layer fruit can be stored for only 4–6 weeks. In both of these fruit stages, the liquid endosperm is sweet and suitable for consumption together with the soft kernel. In the Philippines, young coconut is classified into three stages and referred to as the mucus-like stage, cooked rice-like stage and leather-like stage (Gatchalian *et al*., 1994). The fruit in the leather-like stage are used in bakery and confectionery products. Other indices included:

- The color of the branch (rachillae) of the inflorescence (Plate IIIb) on top of the individual coconut that originally held the male flowers is also use as a maturity index. When it is ready to be harvested the distal half of the rachillae turns from fresh green to dry and brown. However, weather conditions may accelerate or delay this change.
- The color of the peel around the perianth: if it is creamy-white or whitish-yellow the fruit is too young. When the color turns almost green the young coconut is ready for harvest.
- The stage of the bunch above. One can also determine the maturity of the lowest bunch by observing the two bunches above. If the one directly above (20° off) has fruit the size of a milk can and another bunch on top (also 20° off) has fruit setting, the lowest bunch is ready for harvesting (Petchpiroon, 2001).

Tapping the fruit using a fingernail or the blunt end of a knife to determine coconut maturity is also practiced. The mucous-like stage produces a solid sound, while the cooked rice-like and leather-like stages produce hollow sounds

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(Gatchalian *et al.*, 1994). Terdwongworakul *et al.* (2009) reported that the kernel thickness correlated very well with fruit maturity. The maturity can be non-destructively determined with resonant frequency, obtained after tapping the fruit, with very good accuracy of prediction $R^2 = 0.927$.

Mature coconut
The duration after anthesis is also the most common index to harvest mature coconut. They usually become fully mature at 11–13 months. At this stage the peel of the fruit also turns from green or another color to brown and finally gray. When the husk is to be collected for quality fiber the fruit must be harvested a month younger. In this case recording time of flowering is important. Generally when only one fruit of a bunch turns brown, the whole bunch can be harvested (Thampan, 1975).

2.4 Preharvest factors affecting quality

2.4.1 Light

Insufficient sunlight in high density planting causes the fruits to develop only thin kernels particularly during the last four months before fruit maturity. However, the reduction in copra per tree is mainly caused by the reduction in the number of fruit rather than the thickness of the kernels (Ohler, 1984; Srivichai, nd).

2.4.2 Nutrients

In growing areas further inland, it is fairly common for farmers to apply salt to coconut trees to increase production and improve the sweetness of coconut water. Scientific data supporting this practice is lacking. The tree has a high requirement for chlorine which is considered a macro element in coconut. Chlorine fertilization was found to be strongly correlated with copra content per fruit as well as copra per tree (Ochs *et al.*, 1993; Ohler, 1984). Potassium is the dominant element for the growth and development of coconut trees (Child, 1974). High potassium fertilizer is used to increase sugar content of coconut water (Srivichai, nd.). When calcium levels are insufficient, the tree produces fruit with thin, rubbery copra (Ohler, 1984). Sulfur deficiency also causes rubbery copra. The kernel is softer than usual. It does not dry properly resulting in soft, flexible, leathery copra which is often brown in color (Child, 1974; Ohler, 1984).

2.4.3 Cross pollination

Generally the dwarf cultivars are self-pollinated while the tall cultivars are cross-pollinated, giving the dwarf cultivars a higher degree of fruit set. In aromatic 'NamHom' coconut grown in Thailand, it has been reported that cross pollination with other cultivars results in the disappearance of the aroma, a xenia effect (Petchpiroon, 2006).

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2.4.4 Maturity

For young coconut, sugar content in coconut water increases, while titratable acidity decreases with age up to 8 months. After that the content reverses and the kernel may be too thick and too tough to consume as young coconut (Puchakawimol and Jangchud, 2003). The water also becomes more turbid. For the mature coconut, early harvesting results in lower quantity and quality of copra, which is soft, leathery, dark brown, wrinkled and spoils easily during storage. Fruit harvested at 11, 10 and 9 months yields 5, 15 and 33% less copra than that harvested at 12 months. The oil from early harvested fruit is somewhat turbid (Thampan, 1975). Fully mature coconut produces lower quality coir, used for making brushes and cushions. For lighter color fiber with higher tensile strength, used for making ropes and mats, the fruit must be harvested one month before fully mature. The husk must also be used within three days after de-husking (Ohler, 1984).

2.5 Postharvest handling factors affecting quality

2.5.1 Physical damage

Young coconut

During harvesting of young coconut, if the fruit are not carefully handled, the white husk under the green outer skin will be bruised and turn brown (Figure 2.1a). Sulfite treatment after peeling cannot eliminate this browning appearance. Stronger impact causes deeper bruising and may cause cracking of the shell. Our study indicates that a fall of only 5 cm on a hard surface causes a light brown bruising at the depth of 2 cm, while falling a greater distance causes more intense browning. A fall of 20 cm or more causes cracking of the shell. The greater the drop, the greater the damage caused. Dropping of the fruit on another coconut of 5 cm or less showed no bruising, but at 10 cm or more browning of the husk can be observed. More mature nuts can withstand more force before rupture. The rupture force of marketable young coconut ranges 200–400 N (Terdwongworakul *et al.*, 2009)

Mature coconut

At full maturity, coconut can be allowed to drop on to the ground. The husk is strong yet flexible enough to absorb the impacting force and prevent damage to the shell and the endosperm inside. However, after de-husking the nut is subjected to cracking under rough handling. The crack occurs transversely and solely on the stylar half of the nut. However, Bruton (1982) showed that vibration during transportation and compression from the top load had little or no effect on cracking.

2.5.2 Temperature

Young coconut

During the storage of young coconut, Consignado *et al.* (1976), Somboonsup (1985) and Nikrota (1994) reported a decrease in soluble solids content and

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increase in titratable acidity of the water, more so in the trimmed fruit. The changes accelerate at higher temperature, resulting in a sour taste. Maciel *et al.* (1992) reported a similar change in soluble solids content but a decrease in acid content and increasing pH. In the kernel, increasing fat and starch content were recorded along with the kernel thickness and possibly accounted for the rough and mealy texture of the kernel. However, decreasing moisture and soluble solids content were found (Gatchalian *et al.*, 1993).

Mature coconut

Low temperature slows down the development of the embryo underneath the soft eye, reduces the rate of evaporation and suppresses the growth of microbes, hence extending the storage life. Freezing at −3°C kills the embryo and the kernel. The thawed kernel loses its crispiness, and becomes softer and more chewable, without any loss of the coconut flavor. In addition, freezing and thawing make it easier to scrape, shred and squeeze the kernel to make coconut milk (Foale, 2003). Exposure of the fruit to temperature change of more than 8°C within a few minutes or to extreme heat or cold induces nut cracking (Seelig, 1970).

2.5.3 Humidity

Young coconut

Water loss from unpeeled young coconut is about 3% per week in ambient conditions (Consignado *et al*., 1976). After peeling and wrapping with PVC film, the white husk appears shriveled after about 4.5% weight loss. During cold transport weight loss is about 1–2% per week.

Mature coconut

Under the strong shell, water still evaporates from the fruit through the kernel and vascular tissue embedded in the shell and connected to that in the husk. At around nine months after pollination, water begins to evaporate from the nut, leaving an air space that can be detected by the sloshing sound when the fruit is shaken (Jackson *et al.*, 2004). High humidity during storage promotes mold growth along with the growth of the embryo (Ohler, 1984). A 10% loss of the nut due to microbial contamination into the kernel and the water is commonly found (Kusuma Na Ayudhaya, 2009). Bruton (1982) found that cracking of the nut was related to water loss. Waxing the de-husked nut with carnauba and paraffin waxes reduced weight loss by 36 and 64% and reduced nut cracking by 60 and 97%, respectively.

2.5.4 Atmosphere

Young coconut

Although coconut respires very little, it still needs oxygen for respiration. Our experiment with young peeled coconut sealed in vacuum plastic showed an anaerobic respiration and accumulation of alcohol within one day at 2°C. No

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report on the effect of ethylene on coconut was found. It is believed that ethylene has no effect on the quality of the fruit.

Mature coconut
The de-husked mature nut should be waxed or wrapped with plastic film to reduce water loss. However, the soft eye area must not be wrapped in order to avoid fermentation.

2.6 Physiological disorders and pests

2.6.1 Young coconut

As a tropical fruit, young coconut is subject to chilling injury when exposed to low temperatures. Young coconut stored at 13.5°C or lower develop chilling symptoms as a brown outer skin (Wijeratnam *et al.*, 2006). Maciel *et al.* (1992), however, indicated that storage at 12°C for five weeks caused no damage. At 0°C the symptom is observed after seven days (Consignado *et al.*, 1976). On the other hand, if the fruit is partially peeled before storage at 2–4°C for up to six weeks, no chilling symptom is found on the husk. It is not known whether low temperatures damage the kernel and this should be investigated.

Wijeratnam *et al.* (2006) reported the development of *Botryodiplodia* sp. on 70–80% of young coconut held under ambient condition (28+/−2°C), leading to perianth dropping.

In trimmed young coconut, mold of various species develops on the surface and finally appear as black mold. Orange and pink colonies are also observed.

Cracked fruit may occur on the distal half of the fruit due to the high pressure inside. A pressure of 2–3 atmospheres has been recorded in young coconut (Scholander, 1955). Over trimming of the husk increases the cracking, indicating that the husk is helping to keep the shell intact (Fig. 2.1(e)).

Shrunk shell on the eye side is often found in nuts that are too young and have the husk almost completely removed by grinding.

2.6.2 Mature coconut

Disease
Over-mature coconut, especially during the rainy season, including those harvested and held for a long time before shelling, may be attacked by various microorganisms. *Colletotrichum gloeosporioides* Penz. has been reported in Brazil. The early symptoms are dark gray to blackish-brown lesions with black margins, later enlarging to cover the whole fruit. The fruit also showed longitudinal rupture allowing other microorganisms to attack the kernel (Ohler, 1984). Internal grayish-dark and yellowish spotting on the testa of the kernel was reported in the Philippines. The spotted nuts are not suitable for copra or oil making. It has been suggested that this is a physiological disorder (Ohler, 1984).

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Bacteria easily attack the copra, forming a slimy surface, right after nut splitting until the beginning of the drying period when the pulp moisture content is still higher than 20%. After splitting, the pulp should be dried immediately (within four hours), either in the sun or in the kiln (Thampan, 1975). Delay in drying resulted in slimy and reddish coloration of the copra surface.

Before drying to the proper moisture content of around 6%, four kinds of fungi can infect the kernel. White mold of *Rhizopus* sp. on wet copra can be observed as masses of white mycelium. Black mold of *Aspergillus niger* develops well when the moisture content is higher than 12%. Between 8–12% moisture, *Aspergillus flavus* thrives and forms brown and yellow molds. It is the most serious mold of all. The oil loss from the growth of this fungal group may be more than 40%. At 7% and lower moisture content, only green mold is observed including *Penicillium glaucum* Link, *Aspergillus guaucua* and other *Aspergillus*. The green mold grows only superficially (Child, 1974; Thampan, 1975). It should be noted that aflatoxin has been reported in coconut product, hence in preparing copra care must be taken to avoid the growth of *A. flavus*.

Insect damage

Copra insect *Cadra cautella* or *Ephestia cautella* is strongly attracted to the molds thriving on the copra that is not properly dry. The larvae feed on the surface mold, but do not readily attack sound copra. The beetle *Necrobia rufipes* de Geer., commonly known as the 'copra bug', is a small beetle, 3–7 mm long, metallic blue in color with red-brown legs and antennae. A reddish-brown beetle, *Tribolium castaneu* Herbst, a pest of flour and cereal products, and the small dull-brown beetle, 3 mm long, *Carpophilus dimidiatus* Fabricius, may attack the copra. However, these insects do not seriously attack copra of good quality (Child, 1974).

Rodent damage

During storage of mature coconut, rodents may be a problem. Necessary procedures must be arranged to prevent the loss from rodents.

Growth

Under warm temperature and high humidity the moisture may be absorbed into the kernel stimulating the growth of the embryo. It starts with the development of the apical part to form plumule and primary root, while the basal part forms the haustorium (Plate III c) that converts food from coconut water and the kernel for the growth of the new shoot and root (Ohler, 1984).

2.7 Postharvest handling practices

2.7.1 Harvest operations

Young coconut

For young coconut, the whole inflorescence must be harvested. A worker must climb up the tree to cut the inflorescence and take it down or toss it into the water

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channel along the coconut row to avoid bruising. The fruit are transported by the whole inflorescence. Dropping the inflorescence on to the ground not only damages the fruit but also causes loose fruit. It is more difficult to handle the separate fruits.

Mature coconut
For dwarf cultivars the mature nuts germinate in 45–60 days after maturation, hence it should be harvested every month. For tall cultivars an interval of two to three months is recommended since the nut germinates in 70–90 days (de Taffin, 1998). When the trees are still small a machete or scythe can be used to cut the bunch off the tree. In taller trees, fully mature coconuts may be allowed to drop on to the ground if they are slow to germinate. The disadvantage of this procedure is the loss from nuts falling and becoming hidden in the thick ground cover, or loss from theft or from damage by rodents. Other problems are nuts germinating on the tree in certain cultivars, and lack of opportunity to inspect the crown to search for pests (Grimwood, 1975). Harvesting can be done by a worker climbing the tree, sometimes with bare hands and feet, reaching the fruit, checking its maturity, cutting and dropping it down to the ground. In some cases a simple tool is used to help the climber, such as a two-loop rope or ankle ring suspended between the climber's ankles to prevent slipping. One climber can harvest 400–800 fruits or 25–50 trees of two bunches per tree, depending on the height of the tree (Child, 1974; Ohler,1984; Thampan, 1975). In some areas the tree trunks have been incised to make notches at about 0.5 m apart to be used as steps for climbing the tree. Some tie a bamboo stem having short branches to the coconut trunk and use it as a permanent ladder. The most difficult part of the climbing is to get into the crown. The climber must swing out from the trunk over coconut bunches on to the crown. A common method is to use a curved knife attached to the end of a bamboo pole to cut the fruit. With this method a worker can harvest up to 2500 fruits per day in a plantation of 7–10 m tall trees. Harvest is at two-month intervals (Child, 1974; de Taffin 1998; Grimwood, 1975).

In commercial orchards in Thailand and a few other Asian countries, farmers train monkeys of the pig-tailed macaque species, *Macacus nemestrina* or *Pithecus nemestrinus* to harvest the fruit (Ohler 1984; Foale, 2003; Grimwood, 1975). A team of worker and monkey can harvest 700–1000 fruits per day (Ohler, 1984; Siriphanich, 1995). The monkey works on a leash following the signal of the owner to harvest coconuts with the right maturity. The monkey removes the fruit by twisting the individual fruit many times to separate it from the bunch and drop it to the ground. The monkey can also jump from tree to tree, saving time.

After harvest the fruit should be kept in the shade to avoid heat from sunlight that may lead to fruit bursting (Ohler, 1984).

2.7.2 Packinghouse practices

Young coconut
At the packing house, young coconut should be sorted by an expert to determine their maturity. Too young, over-mature, undersized, oversized, cracked and

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misshapen fruits should be rejected. Fruit maturity is determined by the naked eye. Too-young fruit will have less sugar and the shell is thin and subject to cracking during transit. Slightly over-mature fruit may be sweet but the pulp is too hard to consume.

Fruit for local markets can be transported in bunches. Over longer distances and for export markets the fruit must be trimmed to reduce space and weight. In addition the US does not allow coconut with green skin to be imported, for quarantine reasons. The trimming can be moderate to almost completely remove the husk surrounding the shell. The trimming process is done manually, a task which requires skilled labor and is extremely hazardous. Currently, workers must shear the husk off the green fruit with a long sharp knife. The inner white husk is then finely shaped to form an inverted conical shaped top, a slightly tapered cylindrical body, and a flat base (Plate III e–f). The final product has a pentagonal contour (Fig. 2.1 (a)–(b)), weighing two-thirds of the whole fruit. This is the most popular method to trim young coconut in Thailand. The whole process takes less than 1 minute per fruit when done by a skilled worker (Nikrota, 1994). The shortage of experienced labor and the high production cost have created an urgent need for mechanical trimming machines.

Jarimopas *et al.* (2009) developed a prototype trimming machine for young coconut which appeared to have potential. The machine is based on the lathe cutting machine mechanism and is composed of a lathe machine with a body-trimming knife, a shoulder-trimming knife, a base-cutting knife and clamping mechanisms. The prototype had the capacity to trim 86 fruits per hour, about 2.5 times faster than manual trimming. The finished product contains on average 14.5% of untrimmed green area and 0.35% of coarse surface area.

On the other hand, most parts of the husk may be removed by grinding the partially peeled fruit with a motorized grinder, leaving only a knob of husk to protect the soft eye. The weight of this ground coconut is only 35% of the total fruit weight (Nikrota, 1994). If the entire husk is removed the fruit are easily subjected to microbial attack through the soft eye. With this method the shipping weight is much less than the former method. However, the fruit cannot be set still on a flat surface. Other shapes of peeled young coconut do exist as shown in Plate IV B. Peeling off too much husk reaching the shell may result in shell cracking, especially in the round-shaped cultivars. The cracking may occur because of the weak shell that has not developed enough to withstand the pressure inside the fruit, which had been recorded between 2–3 atmospheres in full-sized young coconut (Scholander, 1955).

Immediately after peeling, the fruit is submerged in 1–3% sodium metabisulfite (SMS) solution for about three minutes to avoid browning. SMS treatment bleaches the husk and makes it appear whiter than the natural color of the husk. The solution may contain fungicide to prevent mold growth during long storage or transportation. Thiabendazole is recommended at 500 ppm concentration. After the dipping, the fruit is then wrapped with PVC film, affixed with a brand name sticker (Fig. 2.1(b)) and packed in single layer carton boxes. Carton size is about 8 kg containing 9 to 12 fruits according to the size of coconut. With the above

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(a)

(b)

(c)

(d)

(e)

(f)

Fig. 2.1 (a) Trimmed young coconut showing brown patches after being bruised; (b) Young coconut of different shape after trimming or grinding and wrapped with plastic film; (c) De-husking of coconut fruit using a large pliers-like tool to pierce through the husk and pull it apart; (d) Shelling of coconut fruit using a tool with a chisel end and an axe in the middle; (e) Trimmed young coconut for sale together with a 'cup-saw'. Notice the circumferal crack below the saw; (f) A coconut borer.

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procedure the peeled young coconut can be kept for up to two months at 2°C, but only seven days in ambient condition.

Mature coconut
To reduce space and weight during transportation, the mature fruit must be completely or partially de-husked, leaving the husk about 1–2 cm thick. De-husking is usually done by hand using a spear that is fixed vertically and firmly on the ground. During de-husking the worker holds the fruit horizontally, strikes it near the stem end on to the tip of the spear to make the first incision, then rotates the fruit slightly and strikes again and twists the fruit to push the husk, between the first and the second strike, outward. The process is then repeated to separate the husk into 3–5 chunks. These chunks of husk are then pulled off by hand. A similar procedure can be carried out in the opposite direction as can be seen in Fig. 2.1(c). With this procedure an experience worker can de-husk 2 000–3 500 fruits per day (Child, 1974; de Taffin, 1998). Several de-husking machines have been invented that can remove the husk quickly and efficiently. Demonstration of these machines can be observed on the internet. The nuts that have the husk completely removed are subject to microbial attack perhaps through the soft eye or directly through the vascular tissue embedded in the shell (Foale, 2003).

If the husk will not be used the de-husking should be done in the orchard because amounts of K and Cl removed from the soil are very high. De-husking in the orchard returns the minerals into the soil saving the cost of fertilizer (Ochs *et al.*, 1993). The de-husked nut can be held in bulk, jute sack or plastic mesh bag for local or short distance export markets. The nut may be wrapped with plastic film with a hole around the eyes (Foale, 2003). Film wrapping is intended to reduce water evaporation from the nut while the hole is needed to allow the nut to breathe as well as preventing too high humidity that induces germination. Partially de-husked nut, although keeping longer, is not acceptable in many importing countries because it may be a pest carrier (Foale, 2003).

For copra making the nut is split into two halves by striking it with a sharp machete at its equator (Fig. 2.1(d)). A skilled worker can split up to 10 000 nuts per day. The water should be drained off completely by turning the split nuts face downward for one to two hours (Child, 1974; Thampan, 1975).

2.7.3 Control of ripening and senescence

Young coconut
Young coconut with intact skin can be stored for up to 4 weeks at 12°C (Maciel *et al.*, 1992). At lower temperatures the fruit surface turns brown. Held in ambient conditions, the fruit last for about one week, during which the kernel is still developing. Wrapped fruits are better in quality than the unwrapped and can be stored in good condition for up to five weeks at 12°C. Gatchalian *et al.* (1993) reported that during storage the kernel of young coconut at 7–8 months old

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becomes thicker and firmer, higher in starch and fat content but lower in moisture and soluble solids content. However, changes in titratable acidity and pH have not been observed.

For trimmed coconut, husk browning and mold growth are the main problems. To prevent browning and mold growth, three minutes dipping in 1–3% SMS solution is recommended. Because the use of sulfur on fresh fruit is prohibited in many countries, attempts have been made to find a way to reduce this or substitute SMS. One procedure is to use a solution containing 3.5% ascorbic acid and 2.5% citric acid (Yuwang, 1997). However, its effect on mold growth was not reported. A fungicide may need to be added to the solution. Another procedure uses a combination of 1% SMS and 4% NaCl. This solution gives coconut the natural cream color of the husk and prevents mold growth at 4°C for up to four weeks (Riyakul and Siriphanich, 2006). Hot water (100°C) dip for one minute followed by cold water dip and 1% SMS solution may also be used for storage of young coconut at 10°C for 4–5 weeks (Wattanayothin *et al.*, 2001). Mohpraman (2010) showed that at very high SMS concentrations, the compound could penetrate the husk and the shell into the pulp and coconut water probably through the vascular tissue. However, if SMS solution was 3% or lower and the dipping time was shorter than five minutes no residue was found in the coconut kernel and water. He also demonstrated that SMS could penetrate the husk more easily at the stem end. In addition the soft eye that did not have thick shell covering would allow easy access for SMS. Hence, in peeling the fruit, the husk on the stem side should be kept at least 1 cm thick.

Mature coconut

In mature coconut, the husk is already dry and is not alive. Hence the fruit should not be classified as climacteric or non-climacteric. No procedure is required to control its ripening. However, the seed is alive, developing and will eventually germinate. Good nuts should be heavy with a slight sloshing sound when shaken. Nuts that are light with little water inside are considered old. The color of the husk on the fruit should be brown, not gray, which indicates an old nut (Foale, 2003). To delay the nut development, it should be kept in dry conditions. Bruton (1982) reported that waxing the de-husked nut with carnauba and paraffin reduced weight loss and reduced nut cracking, but did not report their storage life.

2.7.4 Recommended storage and shipping conditions

Young coconut

Whole and intact young coconut is best stored at 13.5°C for up to 4 weeks after which browning of the perianth is observed (Wijeratnam *et al.*, 2006). Storage at 28°C results in turbidity and fermented odor of the water, particularly in split nuts. Young peeled coconut wrapped with PVC plastic can be stored at 2°C for up to 2 months. Pink discoloration of nut water is sometimes observed. The cause of this discoloration is unknown.

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Mature coconut
If the fruit are not fully mature, they should be kept dry in shade for 2–3 weeks to make them easier to de-husk and to remove the kernel from the shell as well as to prevent germination. In addition, when the shell is used for burning as fuel, less smoke is produced (Grimwood, 1975). During storage, moisture content of the kernel decreases slightly, oil content increases, kernel thickness and copra yield increase, and resistance to bacterial sliming increases. The whole fruit can be stored at ambient condition for 3–5 months before sprouting. However, the fruit should be piled above the floor on flats or pallets to minimize insect and rodent infestation as well as to allow better air circulation. Woodroof (1970) reported that mature coconuts could be stored at 2.5°C with 45–55% relative humidity for 2 years. Recommended storage or shipping temperature for mature coconut is 14–16°C. The fruit last for 8 months if the humidity can be kept at 50%.

Dehusked mature coconuts can be stored for 60 days at 0–1.5°C and 80–85% relative humidity, while at 13–15°C and 80–85% relative humidity the nuts last for only 2 weeks (McGregor, 1987). Pre-cooling before loading into shipping containers is not needed since coconuts respire and release very little heat. Too fast cooling may result in cracking of the shell. Waxing or film wrapping to prevent moisture loss is recommended (McGregor, 1987; Foale, 2003).

2.7.5 At the consumer table

To consume young coconut the shell must be cut open. Traditionally, a large sharp knife is used to create an opening of approximately 60 mm in diameter at the top of the fruit. This method is hazardous and requires a skilled operator. To avoid the labor requirements and the risks inherent in this method, there is a high global demand for a tool that is easily used to open young coconuts. Many tools can be found on the internet. Jarimopas and Kuson (2007) developed a young coconut opening machine. The machine works on the concept that opening is achieved by shearing the rotating trimmed young coconut by a stationary knife. The machine performance is about two fruits per minute with 2% juice spill-off, 0.2 g of sawdust in juice, and diameter of circular opening of 58 mm. A ‘cup saw’ was invented consisting of a cup-shaped plastic handle attached to a ring saw (Fig. 2(e)). To open the fruit, the consumer simply saws the top of the fruit in a circular motion until the saw blade reaches the kernel. If only the water will be consumed, coconut borers can be used. An example of the borer is shown in Fig. 2(f).

2.8 Processing

2.8.1 Copra

Copra is the dry coconut kernel, mainly used as raw material for the production of coconut oil. Fully mature nuts are selected for copra production. Nuts are split into two halves with a sharp machete. The kernel is then either removed immediately with a knife or semi sun-dried before removal (de Leon and Delores,

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2004). The water content of coconut meat should be reduced to 35% within 24 hr. During the subsequent 24 hr the moisture content should be reduced to 20%, and finally to 5–6% in the next 24 hr. Using too high a temperature for drying may result in discoloration (browning) of the copra. Drying at high temperature may result in case-hardened copra (dry tissue on the surface), which is not thoroughly dried. The case-hardened copra has a short shelf life and is susceptible to insect and mold attack (Grimwood, 1975). Five methods are used for drying coconuts including sun drying, smoke drying, direct kiln drying, indirect kiln drying and forced-air drying (Malabrigo, 1977; Ranasinghe *et al*., 1980; Patil, 1984). Copra of superior quality (first class copra) is usually produced within 24 hr of nut splitting by forced-air drying or indirect hot-air drying. Roberto *et al.* (1996) reported an optimum temperature of 90°C to dry coconut kernel with the shortest drying time and high quality copra. In some countries, whole coconuts are slowly dried in the shell to produce ball copra. It may take 6–12 months to complete the drying process (Chavan and Jadhav, 1995).

2.8.2 Coconut oil

Coconut oil is used for industrial purposes as raw material for the production of soap and as a medium in the paint and varnish industries. It is also used in the manufacture of methyl esters, fatty acids and fatty alcohols, which are raw materials for detergents, surfactants, emulsifiers and pesticides. For the manufacture of edible products, the crude oil is refined with caustic soda solution, dried and bleached with fuller's earth (International Trade Center, 1990). Standards of coconut oil are included in the Codex standard for named vegetable oils CX-STAN 210–1999 (Codex Alimentarius Commission, 2009). Virgin coconut oil is obtained from the fresh mature kernel by mechanical or natural means with or without the application of heat, which do not lead to alteration of the oil (Asian and Pacific Coconut Community, 2003). Coconut oil is also obtained from extraction of coconut kernel (fresh or copra) using wet milling or dry milling. In wet milling, coconut kernel is disintegrated using a colloidal mill and mixed with a small amount of water before being pressed through the expeller. Dry milling is a conventional method used in the coconut oil extraction industry. The copra is crushed into a fine powder and heated to 104–160°C (Thieme, 1968; Food Market Exchange, 2000). After heating, the oil is extracted using either an expeller or a hydraulic press. The temperature of the oil should be kept at 93–102°C during oil extraction to obtain a high yield and a light color oil. After oil extraction, the oil is screened and filtered to obtain clear oil (Chavan and Jadhav, 1995; Food Market Exchange, 2000). The clear oil may be further processed to remove undesirable colors, flavors and aromas (Foale, 2003).

2.8.3 Desiccated coconut

Desiccated coconut is the grated and dehydrated coconut meat, which is mainly used in the bakery and confectionery industries. The Codex Alimentarius Standard

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for various grades of desiccated coconut (CODEX STAN 177–1991) contains three size classifications: extra-fine, fine and medium (Codex Alimentarius Commission, 1994). Desiccated coconut processing includes selection of nuts, husking, shelling, removing the testa (paring), washing, heating, disintegrating, drying, sieving and packaging (Grimwood, 1975). The fruit are de-husked in the field and transported to the factory. They are then split using a small hatchet or special knife to obtain a complete, undamaged ball. The outer brown testa around the ball is removed using a special knife. The pared kernels are then cut and the coconut water is discarded. The pieces of endosperm are washed with fresh water to remove any remaining coconut water and other debris and to prevent discoloration. The kernel pieces are then pasteurized in live steam for 5 min at about 88°C or for 8 to 10 min at 70 to 80°C. The material is then immersed in sulfite solution for stabilization, followed by grinding or shredding, and drying using a steam-heated dryer, in which the moisture content is adjusted to 2.5–3.0%. After that the product is cooled, graded by size and packed (de Leon and Delores, 2004).

2.8.4 Coconut milk

Coconut milk is an important ingredient in Asian cuisines. It is defined as a milky fluid manually or mechanically extracted from grated coconut kernel with or without the addition of water (de Leon and Delores, 2004). Due to its high content of oil, moisture and organic compounds, fresh coconut milk spoils quickly after extraction (Gonzalez, 1990). Thermal processing is a common method for extending the shelf life of coconut milk. The processing of canned coconut milk starts with the extraction of coconut milk, followed by heating at 92 to 95°C for 5 to 20 min. Emulsifiers and/or stabilizers are added before homogenization. The homogenized coconut milk is either hot-filled in cans or passed through an exhauster before can sealing. Since coconut milk (pH≈6) is considered a low-acid food, it is necessary that the canning process is performed in a retort above 100°C, before cooling and labeling (Timmins and Kramer, 1977; Gonzalez, 1990; Arumughan *et al.*, 1993). Aseptic processing may also be applied for production of ultra high temperature (UHT) coconut milk.

2.8.5 Coconut water

The coconut water processing in Thailand includes heating, mixing with sugar to obtain 9°Brix sugar content, hot-filling in can and seaming. The coconut water then undergoes sterilization at 116°C for 30 min before cooling (DOA, 2009). Frozen coconut water is also produced by pasteurization of coconut water at 90°C for 5 min, hot-filling in plastic bags or cups, cooling and freezing using air-blast facilities. A filtration technique using pre-filtration with a 0.80 μm pore membrane and microfiltration through a 0.20 μm membrane is recommended for production of sterile coconut water without using any heat to maintain natural flavor and nutrients. The sterile product flushed with nitrogen and aseptically packed, with

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added 0.015% vitamin C for color stabilization, has a minimum shelf life of eight months (FAO, 2000a; FAO, 2000b; Satin, 2000).

2.8.6 Coconut gel (*Nata de coco*)

Coconut gel (*Nata de coco*) originated in the Philippines. It is a product made by fermentation of coconut water or dilute coconut milk using *Acetobacter aceti*. The gel is usually preserved in syrup and used as a dessert. Ten to eleven month old nuts are usually selected as raw materials. The optimum fermentation conditions for the coconut water medium are 6% sugar and pH of 3.5, while those for a dilute coconut milk medium are 6 to 8% sugar and a pH of 3.5 to 4.5 (de Leon and Delores, 2004). The pH is adjusted using glacial acetic acid. After mixing all ingredients with mother liquor (starter), the mixture is poured into a mold and incubated at 23 to 30°C for 8–10 days. The gel formed on the surface is separated and cleaned by scraping the white layer off. Then it is cut into cubes, soaked in running water to remove the sour taste and smell, and boiled for 5–10 min in water. After draining, sugar is added to the gel, and the mixture is allowed to stand for 15 hr. After that, water is added and the mixture is boiled for 10 min. This process is repeated the next day. When the gel is completely penetrated with sugar, it is hot packed in sterilized jars and thermally processed to extend shelf life (Sanchez, 1990; Food Market Exchange, 2000).

2.8.7 Roasted coconut

Roasted coconut is a unique coconut product obtained from burning young coconut to create an aromatic and enhanced flavor. The water becomes sweeter and more turbid. The kernel becomes softer and sweeter as well (Jangchud *et al.*, 2007). Young coconuts with thick kernels, eight months after anthesis, are selected as raw material for production of roasted coconut. Traditionally, burning is carried out by placing the whole young nut over the fire until the husk shows signs of burning (45 min to 2 hr). After cooling, the husk is trimmed down to the shell. Bleaching agent is sometimes used in the production of commercial roasted coconuts to prevent surface discoloration. Recently, an alternative procedure for making roasted coconut has been widely practiced. The coconuts are de-husked and soaked in bleaching agent before boiling in water for 25–45 min depending on size. The finishing touch is usually added by exposing the shell to fire for a short period of time until signs of burning occurs (Department of Agriculture, 2009).

2.9 Conclusions

Being a bulky fruit containing an amount of saturated fat, coconut has never been an important fresh fruit commodity. Most fruit sold in the international market is the mature fruit used for processing and cooking in bakery or in hot dishes and desserts of Asian cuisine. Because of the advance in postharvest technology, young coconut

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is now exported across the continents. Its storage life is up to two months at 2°C. However, the handling processes to prepare the fruit are labor intensive. Mechanical tools are needed to replace labor, particularly in trimming the young fruit. Opening of the fruit for fresh consumption is another obstacle preventing home consumption, since it is rather difficult or even dangerous to crack open the hard shell. Hence a home tool is essential to stimulate selling. Improvements are also needed in the procedure to prevent browning and mold growth. Nevertheless, it has been shown that optimum concentration and duration of dipping in SMS solution do not contaminate the water and the kernel, so a course of action to have coconut exempted from the ban on SMS usage, a privilege granted only for grapes (as sulfur dioxide) in many countries, could be another alternative. Last of all, a more rigorous campaign is required to inform the consumer about the benefit of consuming coconut and to counter the false publicity about saturated fats in coconut.

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(a)

(b)

(c)

(d)

(e)

(f)

Plate III (Chapter 2) (a) different shape and color of coconut fruit; (b) a young coconut of 'one and a half layer' stage. Its cross section showing the white portion of the solid endosperm (kernel) at the stylar end and the translucent portion at the stem end. Notice the long rachillae attached to the top of the fruit; (c) germinating mature coconut. Notice the haustorium, the young shoot and root; (d) de-husked coconut showing the three ridges dividing the three carpels on the stylar end, and the three eyes on the stem end of the fruit. Notice the soft eye is in the largest segment; (e) trimming of young coconut beginning with chopping off the green skin; (f) trimming of young coconut followed by slicing off the body of the fruit.

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Plate IV (Chapter 3) Fruit panicles with white immature dabai fruit, turning purplish pink and powdery black colour on ripening.

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3

Dabai (*Canarium odontophyllum* Miq.)

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Abstract: Dabai or *Canarium odontophyllum* Miq. is indigenous to Borneo. The immature dabai fruits are white, turning pink and a powdery black colour on ripening. The fruit is a drupe berry with thin skin (epidermis) surrounding flesh (mesocarp) and seed (endocarp). The fruit shape is oval to ellipsoid, 3–4 cm long and 1.5–2.5 cm in diameter. The flesh varies in thickness from 0.2 to 0.7 cm, the colour ranges from pale yellow to golden and covers a single large three-angled seed. This fruit is served by soaking in lukewarm water (about 50°C) for 15–20 min to soften the flesh. After draining off the lukewarm water, a little salt is sprinkled over to soften dabai fruit before serving. The postharvest physiology and technology information available on this fruit is very limited. The oil content of the fruit flesh contains antioxidant properties and thus it is gaining attention from consumers, growers and researchers.

Key words: *Canarium odontophyllum*, dabai, Sibu olive, oil content, antioxidants, climacteric, water loss.

3.1 Introduction

3.1.1 Origin, botany, morphology and structure

Canarium odontophyllum Miq. belongs to the family Burseraceae of Sapindales order in the Eudicotyledoneae class. The family consists of 16 genera and about 550 species in the tropical regions of both hemispheres (Leenhouts, 1956). The genus *Canarium* contains about 100 species which are mainly found in tropical Asia and the Pacific, and in Africa (Whitemore, 1966; Coronel, 1986; Evans, 1992). More than half of *Canarium* spp. are native to the old world tropics of southeast Asia (Sui *et al.*, 1997).

Canarium odontophyllum is indigenous to Borneo, Sarawak and Sabah (Malaysia), Brunei and Kalimantan (Indonesia), Palawan (Philippines) and Sumatra (Indonesia). It is commonly known as dabai, dabei, dabey, Sibu olive, Sibu canna or tropical olive by locals. In Malaysia, the tree is found naturally

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along river banks in Sibu, Sarikei, Kapit and Limbang Divisions of Sarawak except in swamps and coastal sands.

Dabai is propagated from seed. The dabai tree is tall, medium-sized and with a straight trunk which only starts to branch at a height of about 2–3 m above ground (Kueh, 2003). The tree grows more than 20 m tall with a stem girth of more than 150 cm. The bark is grey-brown. The crown is rounded and dense. The leaves are spirally arranged, 3–8 pairs of leaflets, pinnate with a terminal leaflet. Leaflets are oblong to lanceolate with a length of 9.5–28 cm and width of 4–11 cm.

The dabai plant is androdioecious with staminate and hermaphrodite inflorescences in different plants (Sim, unpublished data). However, flowers with well-developed stamens and under-developed pistils have also been observed. The staminate or male plants bear a long and thin inflorescence with small flowers while the hermaphrodite plants bear a short and thick inflorescence with flowers considerably larger than the male. The hermaphrodite flowers are carried on terminal inflorescence. The male trees start to flower at an early stage of 4–5 years while the hermaphrodite trees start flowering and bearing at a later age of about 6–8 years after planting.

Bud-grafted hermaphrodite plants are recommended to ensure fruit bearing and the trees come into fruit at about 3–5 years after planting. The Agriculture Research Centre in Semongok, Sarawak, Malaysia has selected two superior bud-grafted clones, 'Laja' and 'Lulong', for commercial production (Lau and Voon, 2007). At an early stage of the reproductive phase, a bud-grafted tree can produce 10 kg of fruit and it gradually increases to 80–100 kg per tree when the tree reaches 10 years old and above. A single tree can bring in a gross return of at least MYR 9000.00 (about USD 2571) per annum and a hectare can give a gross return of at least MYR 612 000.00 (USD 174 857) per annum with 12 m × 12 m spacing between trees (Gadug and Yusup, 1992).

The immature dabai fruits are white, turning purplish pink and a powdery black colour on ripening. (See Plate IV in the colour section between pages 274 and 275.) The fruit is a drupe berry with thin skin (epidermis) surrounding flesh (mesocarp) and seed (endocarp) (Wong, 1992). Opening spores distribute themselves randomly and abundantly on the skin surface (Ding and Tee, unpublished data). Fruit shape is oval to ellipsoid, 3–4 cm long and 1.5–2.5 cm in diameter. The flesh varies in thickness from 0.2 to 0.7 cm, the colour ranges from pale yellow to golden and covers a single large three-angled seed. Fruit can be harvested about 120 days after flowering (Voon, 2003). Dabai fruits are normally available from October to January in local markets of the central regions of Sarawak (Sibu, Mukah, Sarikei and Kapit Divisions). The fruit is very popular among the locals and is being recommended to tourists in tourism brochures of Sibu (Anon, 2006) and Miri (Anon, 2009). Besides being eaten by humans, dabai fruit is also consumed by orang utans in the wild jungle of Borneo. (*Pongo pygmaeus*) (Mackinnon, 1974).

Good quality dabai fruits are plump, weighing 18 g per fruit, have a thick and yellow flesh, a good nutty aroma, flavor with a fine creamy texture and taste neutral or with minimum sourness (Lau and Fatimah, 2007). There are different categories and ratings for dabai fruit, with the prices ranging from as cheap as

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Table 3.1 Dabai fruit physical characteristics of 'Laja' and 'Lulong' clones

Physical characteristics	'Laja'	'Lulong'
Fruit weight (g)	18.9	13.9
Fruit length (cm)	4.5	3.6
Flesh thickness (cm)	0.35	0.31
Seed weight (g)	7.7	5.0
Edible portion (%)	61.5	64.0
Shape of seeds	Triangular with concave sides	Rounded with convex sides

Table 3.2 Dabai fruit nutritional values of 'Laja' and 'Lulong' clones

Nutritional values (%)	'Laja'	'Lulong'
Protein	6.8	5.5
Fat	44.3	33.9
Carbohydrate	37.2	45.6
Fibre	8.1	11.6
Ash	3.8	3.4

MYR 8 (USD 2.23) per kg to as high as MYR 24 (USD 6.86) per kg, depending on quality, flesh thickness and taste, visual appearance of skin and season. The physical characteristics and nutritional values of 'Laja' and 'Lulong' clones of dabai fruit are shown in Tables 3.1 and 3.2, respectively (Lau and Voon, 2007).

3.1.2 Culinary uses, nutritional value and health benefits

A fresh dabai fruit is firm with light yellow flesh. This fruit is served by soaking in lukewarm water (at about 50 °C) for 15–20 min to soften the flesh. After draining off the lukewarm water, a little salt is sprinkled over to soften the dabai fruit before serving. The purplish black skin is eaten together with the flesh but not the seed, which is very hard. Sugar and/or soy sauce are also often added to enhance the taste of the fruit. The softened fruit can be eaten as a delicacy by itself or as a side dish with rice and other dishes in a meal. The light yellow flesh turns deep yellow with smooth-creamy texture, rich flavor and oily like an avocado after steeping.

Another way to prepare the fruits is to squeeze out the soft flesh and mash it into a paste. Salt is added to the paste to make it ready for eating. The paste may be preserved in air-tight bottles or containers that will last up to a month or longer in a household refrigerator. The paste can be fried with sliced chillies, onions and anchovy to make it more appetizing. The paste is sold in local markets. Fresh dabai fruit is also preserved in salt or soy sauce and eaten with porridge. In Sibu, Sarawak, dabai fried rice is sold by local hawkers. Recipes for pizza, snack, maki (dried seaweed roll), pitted pickles, desserts and salad dressing based on dabai fruit as well as soap have been developed by the Agriculture Research Centre, Semongok, Sarawak, Malaysia (Bernama, 2008).

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Besides using lukewarm water to soften dabai flesh, there are two other methods used by locals to soften the flesh before serving. One method is to 'sunbathe' the dabai fruit in an inflated polyethylene bag until the flesh is softened. The other method is to store dabai fruit in a freezer and thaw it before serving. The cotyledon of the seed is edible too. The hard seed can be cracked using a mortar and pestle to obtain the greenish cotyledon which is eaten as a nut. It has an almond taste and flavor. Recently, dabai seed was found to have the potential to provide biodiesel that will conform to the biodiesel standards of the European Standard Organization and the American Society for Testing Materials (Razon, 2008).

Dabai fruit is a very nutritious fruit with high energy (339 kcal 100 g^{-1} edible portion), protein (3.8%), fat (26.2%), carbohydrate (22.1%), crude fibre (4.3%), ash (2.3%), phosphorous (65 mg 100 g^{-1} edible portion), potassium (810 mg 100 g^{-1} edible portion), calcium (200 mg 100 g^{-1} edible portion), magnesium (106 mg 100 g^{-1} edible portion) and ferum (1.3 mg 100 g^{-1} edible portion) (Hoe and Siong, 1999). The oil of the fruit contains high antioxidant properties (Azrina *et al.*, 2010).

3.2 Postharvest physiology

Dabai fruit is probably climacteric. The respiration rate of dabai fruit at 20 °C is about 1411 mL CO_2 $kg^{-1}h^{-1}$ and ethylene production is about 4 μL C_2H_4 $kg^{-1}h^{-1}$ (Ding and Tee, 2011). After an exogenous application of 10 mL L^{-1} of ethylene for 24 h at 20 °C, the respiration rate was reduced to 665 mL CO_2 $kg^{-1}h^{-1}$ while ethylene production rate increased to 89 μL C_2H_4 $kg^{-1}h^{-1}$. Treatments with exogenous ethylene and prolonging of ethylene exposure duration were not able to soften the flesh of the fruit, but accelerated fruit senescence and microbial growth in the fruit (Ding and Tee, 2011).

Color components, L*, C* and h°, of mature dabai fruit skin collected from Papar, Sabah, Malaysia, were 25.17, 0.91 and 52.83, respectively. The flesh firmness of dabai fruit before steeping was 201.48 N and decreased tremendously by 92% to 15.74 N after steeping at 60 °C for 15 min (Ding and Tee, 2011). Similarly, the soluble solids concentration increased by 580% after steeping, to 10.95%. The pH of dabai fruit decreased from 5.88 to 5.04 while titratable acidity increased from 0.0033 to 0.0092 % citric acid after steeping. The citric, malic and succinic acids of dabai fruit increased from 67.48, 61.69, 23.79 to 99.72, 71.75, 47.12 mg g^{-1}, respectively, after steeping at 60 °C for 15 min.

3.3 Harvesting

Dabai fruit are harvested when the white young fruit become powdery black. Due to its height, a long bamboo pole with a sickle at the end is used to harvest terminal branches where fruit are borne in panicles. (See Plate V in the colour section between pages 274 and 275.) A net is placed below the canopy to catch dislodged fruits and fruit branches. Damage to the fruit falling off the tree has not being

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studied. Fruit is removed manually from its pedicel in the field and brought to the market in bamboo woven knapsack baskets.

3.4 Maturity and quality components and indices

The information on maturity and quality components and indices is not available.

3.5 Postharvest handling factors affecting quality

The shelf life of dabai fruit is rather short – about 3 days at 27 °C when the skin of hard fruit will wrinkle (Wong, 1992) (Fig. 3.1). Heat is the main concern in handling dabai fruit. Fruit should be harvested during dry weather and in the morning (Lau and Fatimah, 2007). The freshly harvested fruit must be kept in well-ventilated baskets and away from the sun. Heat trapped in baskets could result in fruit being 'cooked' and unmarketable.

There are contradictory findings on the storage of dabai fruit. With storage at 5 °C, the shelf life could be extended (Voon, 2003). It could be extended up to 8 days by packing fruit in polyethylene plastic bags at 14 °C (Jugah, 2006).

Fig. 3.1 Dabai fruits after seven days' storage at 10 °C; wrinkles can be seen on most of the fruits.

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Another researcher reported that dabai fruit stored at 10 °C in polyethylene bags could last only 5–6 days, after which it turned soft and spoiled (Lau, unpublished data). Comparing dabai fruit packed in polyethylene bags and stored at 4 and 8 °C, longer shelf life and less water loss was found in fruit stored at 8 °C than those stored at 4 °C (Jitam, unpublished data).

In another study, dabai fruit were frozen for 6 months using PVC containers, polyethylene plastic bags and vacuum packed plastic, and then frozen fruit were thawed for serving by using hot water at 100 °C instead of lukewarm water (Lau and Fatimah, 2007). The frozen-steeped fruits were found to have poorer physical appearance and less creamy taste than fresh fruit, but their quality was still acceptable. Voon (2003) also reported that coating dabai fruit with a thin layer of edible oil could prevent water loss.

3.6 Conclusions

Dabai fruit is a unique fruit which is eaten in a different way from other fresh fruits. Ethylene could not soften the fruit flesh but accelerated the senescence process. It needs heat to soften the flesh, using either sunlight or lukewarm water. Freezing temperatures soften the flesh, and the locals eat fruit injured by chilling. The oil content in the flesh has been claimed to contain antioxidant properties and thus the fruit is gaining popularity. However, information on postharvest physiology and technology of this fruit is still very limited. Extensive work needs to be carried out to understand this unique fruit, from farm gate until postharvest and processing.

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Plate IV (Chapter 3) Fruit panicles with white immature dabai fruit, turning purplish pink and powdery black colour on ripening.

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Plate V (Chapter 3) Harvesting dabai fruit by placing a net on the ground and climbing up the tree, then using a long pole with a sharp sickle at its end to harvest branches with fruits.

Plate VI (Chapter 4) Barhee (Barhi) dates.

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4

Date (*Phoenix dactylifera* L.)

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Abstract: Dates have been an important basic food for several cultures over thousands of years and they are still consumed widely all over the world, especially in the Middle East and North Africa. Date palms grow in several countries, but the industry is still concentrated in the Middle East and North Africa. Over 7 million tons of dates are produced annually, but only about 10% enters world trade. Dates are a nutritious, high-energy food, consumed fresh, dried or in various processed forms. Fruit of some dry date cultivars are not very perishable, and can thus easily be shipped to distant markets and be stored for prolonged periods. In contrast, the shelf life of some moist (soft or syrupy) date cultivars is limited to a few days unless special care is taken to maintain the cold chain between harvest and consumption sites. However, postharvest losses are high due to diverse physical, physiological, pathological and insect problems. Dates adapt very well to very low temperatures, and therefore storage and shipping at low temperatures is the most important method of maintaining quality. Low temperatures significantly reduce losses of colour, flavour, and textural quality; and delay development of sugar spotting, incidence of moulds and yeasts, and insect infestation; and prevent development of syrupiness and souring of soft, moist dates.

Key words: *Phoenix dactylifera*, postharvest, nutritional quality, health benefits, insects, storage, processing.

4.1 Introduction

Fruits of the date palm, *Phoenix dactylifera* L., have been a staple food for the population of the Middle East and North Africa for thousands of years (Yahia, 2005). The date palm is thought to have originated in Mesopotamia and its cultivation spread to the Arabian Peninsula (Fig. 4.1), the Middle East and North Africa in ancient times. It has been suggested that the Sumerians were the first to cultivate the date palm. They used its fruits as a staple food in the Tigris–Euphrates valley as early as 4000 bc (Al-Baker, 1972; Hussain, 1974; Ait-Oubahou and Yahia, 1999).

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Fig. 4.1 Date market in Saudi Arabia (courtesy of Dr Atef Elansari).

In 2007, world production of dates was about 7 million tons, with the Middle East and North Africa being the major producing regions. The top ten producing countries are Egypt, Iran, Saudi Arabia, United Arab Emirates, Algeria, Pakistan, Iraq, Sudan, Oman and Libya (Table 4.1) (FAO statistics, 2008). The date palm plays an important role in the economic and social life of the Sahara. In the old world, the Near East and North Africa are the region where dates are grown in large quantities. In Europe, the only commercial groves are those at Elche and Orichuella

Table 4.1 Date production ('000 tons) in some important producing countries in 2007

Country	Production (tons)
Algeria	500 000
Egypt	1 326 133
Iran	1 000 000
Iraq	440 000
Libya	175 000
Oman	255 871
Pakistan	680 107
Saudi Arabia	982 546
Sudan	336 000
Tunisia	127 000
United Arab Emirates	755 000

Source: FAO (2008)

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in Spain. In the new world, important date palm plantations are in the Coachella valley of Southern California, in Arizona and in northwestern Mexico, and a few plantings in South America (Ait-Oubahou and Yahia, 1999; Pavez-Wellman, 2007; Wright, 2007). There are also some plantings of date palms in the Australian deserts in Queensland. Outside the regions mentioned above, and when the winters are not too cold for it, the date palm will grow, but will not fruit properly.

Date palms start to bear fruit at the age of 4 to 5 years and reach full maturity at the age of 10 to 12 years depending on local conditions affecting rate of growth and development. Flowers are borne in strands on bunches at the top of the tree. The number of bunches per tree varies from three to ten and each bunch includes hundreds of strands and thousands of individual dates. Average bunch weight varies from 5 to 20 kg. One palm can produce up to 100 kg annually, with some cultivars having average yields per tree of 180 kg (Munier, 1973). Depending on cultivar and area, the flowering to harvesting interval ranges between 6 and 9 months. The flowering period in the Northern Hemisphere lasts from late January to March and ripening starts in July and continues until October–November for late cultivars. The date fruit is a berry with a single seed or pit, oblong in shape, 2.5 to 7.5 cm long, with thick or thin flesh. It is astringent when immature and becomes sweet when ripe. The proportion of seed to flesh, which is an important parameter for fruit quality and classification, varies from 9 to 30%.

There are more than 2000 date palm cultivars in the world (Hussain, 1974; Ait-Oubahou and Yahia, 1999). Popenoe (1973) reported over 1500 cultivars of dates in the world. Over 455 cultivars have been reported in Iraq, and more than 350 in Oman (Laville, 1966; Vittoz, 1979). A large number of these cultivars are propagated by seed. Very few cultivars are grown extensively in major producing countries. Zahdi or Zahidi, Khadrawy, Hillawy, Khustawy, Maktoom, Shalabi, Sukari and Sayer are commonly grown in Iraq; Hayani, Samani, Zaghlol, Saidy and Duwaki are commercially grown in Egypt; Saidy and Bikraari in Libya; Boufgouss, Bousthami, Jihel, Bouskri and Mejhoul or Medjool in Morocco; Deglet Noor (Figure 4.2), Rhars and Deglet Beida in Algeria; Deglet Noor and Ftimi in Tunisia; Halawi, Chichap, Shanker, Barhee (see Plate VI in the colour section between pages 274 and 275), Shahaani and Bureim in India; Anbara, Khalas, Khasab, Ruzeis, Kheneizy, Sukkary, Duwaiki and Khudairi in Saudi Arabia; Kabkab, Sayer and Shahani in Iran; and Jowan Sor, Karba, Kalud and Abdandan in Pakistan. In the US, Medjool (Paulsen, 2005), Deglet Noor, Zahdi, Khadrawi and Hallawi dominate commercial production (Ait-Oubahou and Yahia, 1999; Hodel and Johnson, 2007). In Oman, the main cultivars are Fardh, Naghal, Kamri, Mobsouli and Oum Sila (Vittoz, 1979).

Depending on the flesh consistency and moisture content at harvest when fully ripe, date palm cultivars are divided into three groups, namely soft, semi-dry and dry (Hussein *et al.*, 1976; Yahia, 2004). However, fruit of any cultivar when left on the palm or exposed to excessive curing conditions will lose moisture and develop a hard texture. Other classifications can be found within the same group based on fruit characteristics, size and sugar content. In soft cultivars (like Hillawi, Abada, Amhat, Barhee, Bentaisha, Halawi, Hayany, Honey, Khadrawy and

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Fig. 4.2 Tamar (tamr) stage of 'Deglet Noor' dates.

Medjool or Mejhool), almost all cane sugar (sucrose) is converted into invert or reducing sugars (glucose and fructose) during ripening, with a moisture content > 30%. Dry date cultivars (<20% moisture) include cultivars such as Badrayah, Bartamoda, Deglet Beida, Horra, Sakoty and Thoory. Semi-dry date cultivars (20–30% moisture) include cultivars such as Amry, Dayri, Deglet Noor, Khalasa, Sewy and Zahidi. Both dry and semi-dry dates retain a good amount of sucrose on full ripening, in addition to the reducing sugars.

Deglet Noor (meaning date of the light in Arabic) produces medium- to large-sized fruits with small seeds; the fruits are light in colour, have a delicate flavour and are of the semi-dry type with excellent keeping quality during storage and transport. The fruit are sensitive to rain, which causes them to sour. Zahdi produces very sweet medium-sized fruits which are cylindrical in shape and light golden brown in colour. The fruit can be harvested soft or medium-hard to hard. They keep well during storage at very low temperatures. Hallawi (meaning sweet in Arabic) produces light-coloured, soft, large fruits, which are extremely sweet and honey-like. The skin of the fruit shrivels easily and the fruits are tolerant of high humidity. Khadrawi (meaning greenish in Arabic) produces soft, high quality fruits which mature early, tending to reach a dark colour at full maturity, and have a short storage period. Sayer, one of the most widely grown cultivars for commercial use, is not of high quality and has no distinctive flavour. The fruit are very mealy and the syrup is drained out or extracted commercially for sugar production. Medjool produces very large fruits (with proper fruit thinning) with a medium-soft texture and amber colour at maturity. The fruit have a thick flesh, are rich in flavour with a delicious taste, and keep well during storage and transport at low temperatures. Barhee (Plate VII) produces soft sweet fruits with excellent quality, appropriate

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flesh thickness and a cylindrical shape, maturing to a dark brown colour. Khustawi fruits have good eating quality, are soft and very juicy, thus requiring good curing, and keep well in storage. Maktoom produces large fruits which are soft with a thick flesh and mature to a brown colour. Fruits of Amir Hajj mature mid-season and are of high quality, soft with a delicate skin but thick flesh and can withstand high moisture. Deglet Beida produces light-coloured fruits, with a smooth skin and hard texture, which mature earlier than Deglet Noor fruits. Kush Zebda produces fruits with long fruit stalks, superior fruit quality and a distinctive rich flavour. Tadala produces semi-dry, large fruits which are attractive, brown-to-amber in colour, mature early and have moderate tolerance to moisture in storage.

Dates are consumed fresh, dried, or in various processed forms. They are often consumed fresh after picking especially at the ripe stage ('rutab' stage). In some cultivars, fruits are consumed at the physiological maturity stage ('khalal' stage). Most dates, however, are consumed at the fully ripe ('tamr' or tamar) stage. The fruits at this stage are characterized by very low moisture content and therefore are ideal for long-term storage to be consumed out of season. Losses during harvesting and postharvest handling and marketing are high in most producing countries due to the incidence of physical, physiological and pathological disorders and to insect infestation.

4.2 Fruit growth and development

Flowers have three carpels but on pollination only one develops and two abort. The shape of the fruit is usually more or less oblong or ellipsoidal. The seed, or pit, is bony and cigar-shaped, slightly pointed at the ends, from grey to brown in colour, and with a small embryo. The seed of the date palm fruit is unusual in that it stores the food materials for the developing embryo not as starch, but as hemicellulose.

4.2.1 Pollination

Pollination is one of the most important pre-harvest factors affecting fruit quality in the date palm (Al-Delami and Ali, 1969). The date palm trees are dioecious, with male and female flowers on separate trees. In commercial plantation, the female trees are artificially pollinated (hand or mechanical pollination) with pollen from male trees. Selection of a good pollinizer is of prime importance in the date palm, as the type of the pollen parent affects fruit size and time of fruit ripening, as well as the chemical composition of the fruit. Such effects of the pollen parent on various aspects of date fruit development are referred to as mataxenia (Abbas, 1997a).

4.2.2 Fruit set

Fruit set in the date palm is closely related to the pollen viability as well as temperatures prevailing during the pollination period. Good fruit is usually

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obtained when daily temperature is in the range of 23.9–26.2°C (Nixon and Carpenter, 1978). Poor fruit set resulting from low temperature can be improved by covering flower clusters with paper bags at the time of pollination (Rygg, 1975). A fruit set of 50–80% is considered sufficient to obtain a full crop.

4.2.3 Fruit thinning

Fruit thinning affects postharvest quality (Ait-Oubahou and Yahia, 1999). It is essential to ensure adequate flowering in the following year, to reduce or prevent the phenomenon of alternate bearing, to improve fruit quality and to promote fruit ripening and to reduce compactness of fruit bunches. Thinning can be done manually or by the use of growth regulators. Manual thinning is more common and involves removal of some bunches and/or some strands from each bunch and/or shortening the length of the strands. However, removal of some fruits from each strand is the best method of fruit thinning, but it is very expensive. The easiest method of fruit thinning is to remove a number of spathes or inflorescences and balance the number of bunches with the number of green leaves on the tree (Rygg, 1975). Various growth regulators have been used as thinning agents in the date palm, such as auxins (NAA, 2,4-D) and the ethylene releasing compound, ethephon, but with variable results, and therefore manual fruit thinning is still the widely used practice (Nixon and Carpenter, 1978; Rygg, 1975).

4.2.4 Factors affecting fruit development and ripening

Temperature

For proper date fruit ripening on the date palm, it is essential that the growing season is hot and free of rainfall during the ripening period. The average optimal daily temperature from blossoming until fruit ripening is around 21°C for early ripening cultivars, 24°C for mid season cultivars, and 27°C for late ripening cultivars. The number of heat units (degree days) needed to ripen the fruit varies with cultivar and ranges between 2100 and 4700 for early and late ripening cultivars, respectively. Temperature also has a significant effect on fruit quality. Deglet Noor fruit produced during seasons when the maximum daily temperature during April and May exceeded 37°C were of dry texture and had high acid content and a high percentage of sucrose, and lacked the bright colour characteristic of high quality fruit. In general, fruit produced with 101 heat units in April–May were of excellent quality, but when the heat units were in the range of 147–234, dry textured, low quality fruit were produced (Rygg, 1975).

Relative humidity and rainfall

High rainfall and humidity during blossoming or later stages of fruit development may limit the production of date palms to the same degree as insufficient heat units (Ait-Oubahou and Yahia, 1999). High humidity and rainfall during later stages of fruit development may cause certain physiological disorders.

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Furthermore, low relative humidity (RH) during the ripening period may cause some physiological disorders. High humidity and rainfall have a pronounced effect on the process of pollination. Early rainfall during flowering in the spring may cause the infection of the closed spathes with inflorescence rot. Date cultivars vary in their susceptibility to this disease, with cultivars such as Hillawi and Zahdi being very resistant, and Khadrawi and Sayer very susceptible.

Mineral nutrition

The date palm tree requires high nitrogen for good growth and productivity, and it is less sensitive to other mineral nutrients such as iron and boron, as compared with other fruit trees such as citrus (Mater, 1991).

4.2.5 Fruit growth pattern

As already mentioned, the date palm is a dioceous tree and thus requires cross pollination, which occurs naturally or may be done artificially. The normal date palm fruit is a berry which results from the ovary (Mater, 1991). After pollination and fertilization, fruit growth follows a sigmoidal curve, and is usually divided into five stages of development known by their Arabic terms: ‘hababouk’, ‘kimri’ (kimri, jimri), ‘khalal’ (balah, bisr), ‘rutab’ and ‘tamr’ (tamar) (Figure 4.2) (Abbas and Ibrahim, 1996; Ait-Oubahou and Yahia, 1999; Yahia, 2004). The ‘hababouk’ stage starts after fertilization and is characterized by the loss of two unfertilized carpels. This stage is sometimes included in the next stage. The colour of the fruit at this stage is creamy to faint green. ‘Kimri’ is the immature green stage, characterized by high water content and a rapid gain in fruit weight and size. This stage lasts about 9 weeks depending on cultivar and location. ‘Khalal’ (Plate VII) is the mature full-coloured stage, which lasts about 4 to 5 weeks, and results in a slight decrease in fruit weight and size, as well as in starch content. The colour of the fruit changes from green to yellow, pink or red, or yellow spotted with red, depending on the cultivar. During the ‘rutab’ (soft or moist) stage, the fruit softens, changes colour to light brown, and starts to lose weight and accumulates more sugars (mainly reducing sugars). During the ‘khalal’ and ‘rutab’ stages, the fruit progressively loses water, and starch is converted to sugars. The ‘tamr’ (the Arabic word for dates) is the fully ripe stage of development, when the fruit loses more moisture and gains more sugars, thus attaining a high sugar:water ratio (depending on the cultivar). Most dates are harvested at the ‘tamr’ stage (Fig. 4.2), when the fruit has about 60 to 80% sugar content, depending on location and cultivar. At this stage, fruit can be harvested soft, semi-dry or dry depending on destination and use. Dates can also develop parthenocarpically if not pollinated. However, these fruits will not undergo the five stages described above and will not reach full development.

4.2.6 Effect of growth regulators on fruit and development

The early period of date fruit development is associated with a rapid rate of cell division activity particularly in the embryo and endosperm (Rygg, 1975).

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However, the major increase in fruit size is achieved by the vacuolation (enlargement) of the cells formed during the early phase of mitotic activity. Auxins and gibberellins, sprayed onto fruit bunches, have been found to increase fruit size and delay fruit ripening, with inconsistent effects on fruit chemical composition (Rygg, 1975; Nixon and Carpenter, 1978; Abou-Aziz *et al.*, 1982; Mater, 1991). Indole acetic acid (IAA) was found to be very high in non-pollinated flowers of Hallawi dates, declines at fruit set, increases again as the fruit enters the rapid phase of growth, then declines as the fruit advances towards the ripening phase (Abbas *et al.,* 2000). The tendency of the date palm flower to set parthenocarpic fruits if not pollinated may be related to levels of endogenous hormones in the ovary of unpollinated flowers. Parthenocarpic date palm fruits may also be obtained by treating unpollinated flowers with auxins, gibberellins or cytokinins. Such fruits are of low quality as compared to fruits produced by hand pollination and they will not ripen fully (Abou-Aziz *et al.*, 1982). Fruit ripening is usually delayed in trees carrying a heavy crop, which can be remedied by fruit or bunch thinning at an early stage of growth, with the objectives of balancing the number of green leaves and the number of fruiting bunches. Pre-harvest treatment of date fruit of several cultivars with ethephon at 100–500 ppm advanced fruit ripening by 7 to 9 days, and also provided an opportunity for mechanical harvesting of the fruit by facilitating fruit drop.

4.2.7 Biochemical changes during fruit growth and maturation

During the khimri stage the fruit is still green, contains maximum moisture content, a small percentage of sugars and high percentages of tannins and fibers, and therefore the fruit is not edible. As the fruit enters the khalal stage, the green colour is lost and the fruit starts acquiring the distinctive colour which may be yellow, pink, red, or orange, depending on the cultivar. The loss of chlorophyll and the appearance of the distinctive colour is associated with a rapid translocation of sucrose to the fruit, and during this stage the fruit fresh weight reaches its maximum value. Also during this stage, dry matter content and fruit firmness are increased, whereas tannins are reduced.

At the end of the khalal stage, the intensity of the distinctive colour is increased and the fruit starts to soften, as it enters the rutab or ripening stage (rutab literally means softening stage). Date fruit undergoes various physical and biochemical changes during ripening (Rygg, 1975). Softening of the fruit at this stage usually starts at the apical end and ripening progresses inwards and towards the basal end and until the whole fruit is ripe. At the rutab stage, the fruit loses the colour of the khalal stage and starts acquiring a light brown (amber) or dark brown or black colour, depending on the cultivar. The fruit also loses moisture and the size is reduced. The water content of the flesh decreases during fruit development and ripening. In Deglet Noor fruit, for example, the moisture content decreases from about 85% at the early khalal stage to 45% at the beginning of the rutab stage and is only 20% at the tamr stage. The skin surface is generally smooth from fruit set up to the khalal stage, and shows shrivelling or wrinkles as the fruit reaches

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maturity, as a direct consequence of moisture loss. In some cultivars, softening occurs slowly and gradually, while in others it occurs rapidly. Fruit picked at the rutab stage are usually highly perishable and require refrigeration.

If fruit are left on the tree and are not picked at this stage, then they enter the last, tamr stage. At this stage, both fruit fresh weight and size are reduced due to the continuing loss of moisture and the halt in the translocation of sugars. During the tamr stage, the intensity of dark colour increases, with no further changes in fruit weight, size, moisture content and sugars. The texture of date fruit at the tamr stage depends on the percentage of dominant sugars. It is dry if the fruit contains a high percentage of sucrose and the cultivars are called dry dates. However, if most of the sugars are inverted into reducing sugars (glucose and fructose), then the texture is soft and the cultivars are known as soft dates. If the fruit contains some sucrose as well as reducing sugars, then they are called semi-dry dates. Such classification of dates was found to depend on the activity of the enzyme invertase (Cook and Furr, 1952; 1953).

Several studies (Hasegawa and Smolensky, 1970; Hasegawa and Mair, 1972) have shown that the activity of invertase starts to increase as the fruit changes colour from green to the distinctive colour at the end of the khalal stage, and then increases sharply. As the fruit enters the rutab stage and the process of softening is completed, the activity of invertase decreases rapidly and reaches a minimum at the tamr stage. Postharvest induced softening of Deglet Noor dates was achieved by treating the fruit with invertase, causing 50% increase in reducing sugars as compared to control. Polygalacturonase activity was very low at the khimri stage, but increased rapidly as the fruit entered the khalal stage, reaching maximum value as the fruit entered the rutab stage, but thereafter, the activity declined rapidly (Hasegawa *et al.*, 1969). The use of this enzyme for the artificial ripening of some date cultivars was reported by Hasegawa and Mair (1972). Cellulase activity was found to be low in fruit at the khimri stage, and increased as the fruit advanced in maturity, reaching a maximum value at the end of the khalal stage (Hasegawa and Smolensky, 1971). Studies carried out by Al-Jasim and Al-Delaimy (1972) on several Iraqi date cultivars showed that pectinesterase activity increased as the fruit changed from khalal to rutab stage, followed by a rapid decline as the fruit became fully ripe (tamr). Commercial preparations of synthetic enzymes have been used for artificial ripening as well as to reduce the damage caused by some physiological disorders, such as hard nose, mixed green and sugar walls. For example, a commercial preparation, pectinase, known as Pectino-42, has been found to be effective in reducing the damage caused by the physiological disorder 'mixed green' (Smolensky *et al.*, 1973). Vacuum infiltration with cellulase at 0.1% for 2 hours was very effective in softening Deglet Noor dates and improving quality (Smolensky *et al.*, 1975).

Date flesh texture is an important factor determining quality. Texture changes during fruit ripening from crisp to soft, except for dry cultivars which develop a hard texture after the loss of water content from the flesh. Fruit softening is related to the activities of polygalacturonase, pectinesterase and cellulase (Al-Jasim and Al-Delaimy, 1972; Coggins *et al.* 1968; Hasegawa and Smolensky, 1971;

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Hasegawa *et al.*, 1932; Hasegawa *et al.*, 1969). Invertase was also found to play an important role in fruit softening as it converts sucrose into reducing sugars with the release of water molecules (Coggins and Knapp, 1969; Hasegawa and Smolensky, 1970). Hasegawa and Smolensky (1970) reported that the onset of cellulase, polygalacturonase and invertase activity was found to be correlated with fruit ripening in Deglet Noor and that invertase activity is higher in soft dates than in dry dates. This increase in invertase activity is stimulated by the loss of membrane integrity, which leads to direct contact of the substrate with the enzyme.

Fruit of all date cultivars are astringent at the immature green (khimri) stage due to the presence of tannins. In a few cultivars, such as Barhi, Samani and Zaghlol, the astringency disappears with the change in colour to yellow, orange, or red at the khalal stage. Dates contain significant levels of procyanidins or condensed tannins (the cause of astringency) at the khalal stage. These tannins, which are mainly in the skin, are polymerized as the fruit ripens to the rutaband tamr stages. The intensity of colour in fruit depends on the pigments produced by different browning reactions (Maier and Schiller, 1961). Vandercook *et al.* (1980) and Maier and Metzler (1965) discussed different systems of formation of brown colour pigments in dates and concluded that browning is due to oxidation of polyphenols and tannins. Temperature, moisture content and maturity affect the rate of colour change.

Dates are the only fruit in which flavonoid sulphates have been reported. Hong *et al.* (2006) identified 13 flavonoid glycosides of luteolin, quercetin and apigenin and a combination of some flavonol glycosides with sulphate residues in khalal stage Deglet Noor dates.

4.3 Nutritional components and health benefits

The fruit of the date palm has been a staple food in the Middle East and North Africa since the first recorded history. Date palm fruits were found to contain carbohydrates (44–88%), sugars (60–80%), fats (0.2–0.4%), proteins (2.3–5.6%), fibres (6.4–11.5%) (Hasnaoui *et al.*, 2010; Chaira *et al.*, 2007; Al-Shahib and Marchall, 2003). Dates are considered an excellent source of readily available energy supplying 160–320 kcal $100\,g^{-1}$ depending on moisture content (Ait-Oubahou and Yahia, 1999). The fruit are also rich in Fe, K, Ca, with small amounts of protein (2%), lipids (less than 2%), Zn, Cu, Cl, S and vitamins A, B1, B2 (Nixon and Carpenter, 1978; Rygg, 1975; Vandercook *et al.*, 1980). The crude fibre, which contains pectin, lignin, hemicellulose and cellulose, represents about 2–4% of fruit dry weight. Pectin plays an important role in date texture (Hussein *et al.*, 1976). Fruits of soft, semi-dry and dry cultivars have about 1.0, 1.8 and 1.5% pectins (dry weight basis), respectively, which decrease as the fruit ripen (Rouhani and Bassiri, 1976). The protein content of dates, which is reported to be of high nutritive value, ranges between 1.5 and 2.0%, and the crude fat content ranges between 2.5 and 7.4%. The seed oil is composed of 45% oleic, 25% palmitic, 10% stearic and 10% linoleic acid, with some capric and caprylic acid

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content. The quantities of sucrose and reducing sugars, which are related to quality and texture, depend on the cultivar and fruit maturity and ripeness stage.

Dry and semi-dry dates are rich in sucrose, while most, or in some cases all, of the sucrose in soft dates is converted to reducing sugars (glucose and fructose), so they have a very low sucrose content or contain no sucrose at all. In a study of 12 date cultivars produced in the United Arab Emirates (Ahmed *et al.*, 1995), glucose and fructose levels increased rapidly throughout the developmental stages. The sucruose in Rhars dates in Algeria and Boufgouss and Mejhoul (Medjool) dates in Morocco is entirely hydrolysed to reducing sugars and thus they contain no sucrose at harvest (Munier, 1965), whereas in Deglet Noor, sucrose remains the dominant sugar at harvest (Djerbi, 1996).

The glucose:fructose ratio in Deglet Noor fruits grown in California has been reported to be 1.28 (Coggins *et al.*, 1968). Yusif *et al.* (1982) found that fruit of the cultivars Hallawi, Sayer, Khadrawy and Zahdi in Iraq had glucose:fructose ratios of 1.17, 1.17, 1.16 and 0.83, respectively. Total sugars (reducing sugars and sucrose) increase during fruit development. Deglet Noor fruits have total sugars and sucrose contents, respectively, of 13 and 8% at the khimri stage, 60 and 40% at the khalal stage, and 77 and 53% at the rutab stage (Djerbi, 1996). Starch content, found mainly during the khimri and khalal stages, is converted to sugars and no starch is found at the ripe (rutab and tamr) stages (Djerbi, 1996).

The flavour and quality of dates are affected by their organic acid content. The acidity of the fruit tends to increase with fruit growth and then decreases at the beginning of the ripening stage, while pH increases at maturity. A high pH value is an indication of high quality in dates. Date acidity reaches the highest level during the period of most rapid growth and decreases during maturation and ripening (Rygg, 1975). Rouhani and Bassiri (1976) reported that titratable acidity decreased from 7.7 at the immature stage to 1.4 meq 100 g^{-1} dry weight at the mature stage, and pH increased from 5.1 to 7.0 between these stages. Palmitic acid is the most dominant acid followed by capric and caprylic acids. In Deglet Noor dates, pH changes from 5.5 at the khimri stage to 6.2 at the rutab stage (Djerbi, 1996). Rouhani and Bassiri (1976) reported the same observations for cv. Shahani grown in Iran. The authors found that pH increased from 5.1 to 7.0 with fruit ripening, and acidity decreased from 7.7 to 1.4 meq 100 g^{-1}. In six date cultivars in Iran, fruit acidity remained relatively high and ranged from 2.5 to 4.4 meq 100 g^{-1} (Ejlali *et al.*, 1975).

Date fruits at the fully mature stage are rich in functional components, including phenolic compounds (Al-Farsi *et al.*, 2005; Al-Farsi and Lee, 2008; Hussein, 1970; Sawaya and Mashadi, 1983; Al-Ogaidi and Mutlak, 1986; Regnault *et al.*, 1987; Ramos *et al.*, 1997; Modafar *et al.*, 2000; Al-Abid, 2003; Ishurd *et al.*, 2003; Allaith *et al*, 2008; Biglari *et al.*, 2008; Saafi *et al.*, 2009). Tannins, which are the most dominant phenolic compounds in date fruits and are closely associated with the fruit ripening process, decrease from a high level in the khalal stage to reach minimum concentration in the ripe (rutab and tamr) stages (Rouhani and Bassiri, 1976; Sawaya and Mashadi, 1983). Antioxidant activity varies among date cultivars from moderate to high relative to other fruits. Several studies have

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indicated that the aqueous extracts of some dates have potent antioxidant and antimutagenic activity (Alhumaid *et al.*, 2010; Mansouri *et al.*, 2005; Mohamed and Al-Okabi, 2004). Dates were reported to have the second highest antioxidant activity among 28 fruits commonly consumed in China (Guo *et al.*, 2003).

4.4 Postharvest physiology

4.4.1 Respiration

The respiration rate of dates is very low, < 5 mg CO_2 kg^{-1} h^{-1} at 20°C at the khalal stage, and < 1 mg kg^{-1} h^{-1} at the rutab and tamr stages, and increases with higher moisture content (Yahia, 2004). Cured Deglet Noor dates with 20–22% moisture produced 0.4 mg CO_2 kg^{-1} h^{-1} at 24°C, and 2 mg CO_2 kg^{-1} h^{-1} when the moisture content increased to 27% (Rygg, 1975). The rate of CO_2 production is high initially, but declines steadily as the fruit advances in maturity, reaching its lowest level as the fruit enters the stage of physiological maturity, and then increases to reach a peak as the fruit ripens (Abbas and Ibrahim, 1996). Rouhani and Bassiri (1976) found that the respiration rate of Shahani dates was high during the early stages of fruit development and decreased sharply as the fruit entered the ripening phase. Seed respiration accounts for about 20% of gas exchange in whole dates (Rygg, 1975). Most reports indicate that dates are non-climacteric (Biale and Young, 1981; Yahia, 2004; Ait-Oubahou and Yahia, 1999), although Abdul-Latif (1988), working with three date cultivars (Zahdi, Derey and Sultani), and Taain (1997) on Braim dates, claimed that the fruit is climacteric. Parthenocarpic fruit of Hillawi date did not experience the climacteric rise in respiration during development (Abbas, 1997a). Treatment of date fruits of several cultivars with ethephon was reported to increase the respiration rate and advance ripening (Rouhani and Bassiri, 1997).

4.4.2 Ethylene production and responses

Dates produce very low concentrations of ethylene; less than <0.5 μL kg^{-1} hr^{-1} for khalal stage dates and less than 0.1 μL kg^{-1} hr^{-1} for rutab and tamr stage dates kept at 20°C (Yahia, 2004). Ethylene production in Hallawi dates was not detected until 91 days after pollination, increased to reach a peak within 15 days and then declined rapidly (Abbas and Ibrahim, 1996). There is no effect of exposing khalal stage, yellow Barhee dates to 100 ppm ethylene for up to 48 hours at 20°C and 85–90% RH (Ait-Oubahou and Yahia, 1999). However, khalal stage dates may respond to ethylene action at higher temperatures (30–35°C), which are optimal for their ripening (Kader and Hussein, 2009). Rutab and tamr stage dates are not influenced by exposure to ethylene (Yahia, 2004; Ait-Oubahou and Yahia, 1999). Application of ABG-3161 (an ethylene blocker) at 3.33 g L^{-1} significantly inhibited ripening of Helali dates, suggesting that ethylene has a role in fruit ripening (Awad, 2007).

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4.4.3 Responses to modified (MA) and controlled atmospheres (CA)

MA and CA have been investigated for maintaining date fruit quality and for insect pest disinfestation (Al-Redhaiman, 2005; Baloch *et al.*, 2006; Navarro *et al.*, 2001). An elevated carbon dioxide concentration is fungistatic (inhibits growth of fungi), but once the dates are transferred to air, the fungal growth will resume, especially under higher temperatures (Yahia, 2009). Thus, it is important to market khalal dates stored in MA/CA soon after removal from storage. Packaging tamr dates in low-oxygen atmospheres (using vacuum packaging or nitrogen) can be useful in quality maintenance and insect control (Yahia, 2009). Navarro *et al.* (2001) reported that use of CA during ambient temperature storage is feasible to control insect pests and maintain the quality of dates for 4.5 months. Hallawi, Hadrawi, Zahidi, Derei and Ameri dates were stored in a CA containing 60–80 kPa CO_2 for 4.5 months with no significant changes in peel sloughing and sugar formation on fruit surface, and quality of CA-stored dates was as good as those stored in normal air at −18°C (Navarro *et al.*, 2001). Fruit quality of mature Barhi dates stored at 0°C under CA containing 5 or 10 kPa CO_2 (balance air) was maintained for 17 weeks against 7 weeks in air, while increase in CO_2 to 20 kPa was more effective for maintaining fruit colour, firmness, soluble solids and total tannins for 26 weeks (Al-Redhaiman, 2005). The degradation of caffeoylshikmic acid (CSA), one of the major phenolics undergoing losses during ripening, was also retarded greatly by CA containing 20 kPa CO_2 which suggested that CA was very effective in retarding the ripening process in dates. Fruit having lower levels of water activity (0.52 a_w) were stable for 4 months when stored under nitrogen atmosphere at 40°C (Baloch *et al.*, 2006). The storage of fruit in air or oxygen atmosphere resulted in an increase in skin darkening and titratable acidity during storage; the same effects were also observed with an increase in the water activity of fruit (Baloch *et al.*, 2006). The tolerance of dates to high CO_2 has been exploited to develop biologically safe alternatives to fumigation treatments to control storage pests (Navarro *et al.*, 2001). Rygg (1975) suggested inert gas or vacuum packing for storage of high-moisture dates. Vacuum packaging was found to be useful for reducing darkening of dates during long-term storage (Mohsen *et al.*, 2003). Browning was inhibited at low oxygen atmospheres (Mutlak and Mann, 1984). Further research is needed to investigate the effects of different atmosphere regimes on the quality of dates harvested at different maturities and with different moisture levels.

4.5 Maturity and quality indices

4.5.1 Maturity and harvesting indices

The stage of maturity at which the fruit are harvested depends on the cultivar and the purpose and intended day of fruit consumption. Time of harvest is based on sugar content, moisture content, date appearance and texture. Dates for immediate sale are often harvested when moisture content is still high, whereas dates to be stored are left on the palm for natural curing to lose excess moisture. As mentioned

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above, maturity stages of dates include hababouk (earliest stage of development), khimri, khalal (Plate VI), rutab and tamr (Fig. 4.2). A few date cultivars rich in sugars and low in tannins, such as 'balah' in North African countries, 'bisr' in Oman, Barhee (Barhi, Berhi), Hayany, Samany and Zaghlol, are harvested at the khalal stage (partially ripe) when they are yellow or red (depending on cultivar), but many consumers find them astringent (due to high tannin content). Dates of other cultivars harvested before full maturity must be ripened artificially. Very immature dates cannot be properly ripened artificially and consequently will be of poor quality. Most dates are harvested at the fully ripe rutab (light-brown and soft) and tamr (dark-brown and soft, semidry, or dry) stages, when they have high levels of sugars, lower amounts of moisture and tannins (disappearance of astringency), and are softer than the khalal stage dates. Deglet Noor fruits should not be harvested before the turning stage in which the texture is yielding-to-pliable and the colour is amber-to-cinnamon. Fruits harvested with a reddish ring at the perianth end have better storage potential than fruits left on the palm until the ring has faded with more advanced maturity (Rygg, 1975). Hallawi fruits should not be harvested before the soft ripe stage, but can also be picked in the tamr stage. Maktoom and Boufgouss fruits can be harvested when 10–25% of the surface is translucent, and then ripened to an acceptable quality.

A number of physical and chemical changes have been assessed as indices of maturity and harvesting (Ait-Oubahou and Yahia, 1999), including the increase in total sugars, total soluble solids, colour changes from green to yellow or red or orange or purple according to the cultivar, the rapid fall in fruit firmness, the sharp decrease in moisture content, the increase in reducing sugars and the decrease in sucrose, as well as the decrease in acidity and loss of tannins. The possibility of using the rise in ethylene production as a physiological indicator of maturity in Hillawi dates was also assessed, and the results showed that the rise in ethylene production began in 7–10 days (depending on the type of the pollen parent used in pollinating the female flowers) before fruit ripening (Ibrahim, 1996).

4.5.2 Quality indices

Quality characteristics and criteria

The date is a berry with a single seed that varies in size from 9 to 30% of the fruit weight; a smaller seed or pit and thicker flesh are preferred. Dates may be round, oval, oblong or cylindrical in shape, depending on the cultivar (Ait-Oubahou and Yahia, 1999; Yahia, 2004).

Quality characteristics depend on cultivar, type of date (soft, semi-dry or dry) and condition (whole, pitted, pieces or macerated dates). For fresh dates, high quality is attributed to dates with adequate size and colour, small pits, thick flesh, freedom from dirt, sand or leaf particles, no evidence of bird, insect or rodent damage, no fungal or mould infection, no sugar crystals formation and freedom from any other apparent alterations. The skin of dates should be smooth, with little or no shrivelling, and golden-brown, amber, green or black in colour,

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depending on the cultivar. The texture may be soft and syrupy, or firm or dry, depending on the cultivar. In general, texture and flavour are considered the most important indices of quality in dates. Colour is a good quality attribute in light coloured cultivars. Sucrose is the main sugar in some cultivars (most of the semi-dry and dry cultivars), while reducing sugars (fructose and glucose) are predominant in others (most of the soft cultivars). Total sugars represent about 50% (fresh weight basis) or 75% (dry weight basis). The fact that consumers vary in their preferences for degree of sweetness should be considered when targeting each cultivar to a specific market and in developing products that combine dates with other foods to reduce their sweetness or balance it with acidity when desired (Kader and Hussein, 2009).

The quality of dates is influenced by various factors before harvest, and from the time of picking until the product reaches the consumer. Some of the pre-harvest practices that influence date quality at harvest include covering fruit bunches with paper bags to shelter them from dust, pests and rain (Fig. 4.3), and fruit thinning to reduce compactness of the bunches and increase fruit size and quality (Yahia, 2004). Quality of dry dates can be improved either by curing or hydration. On the other hand, quality of soft dates can be improved to a large extent by dehydration.

Standard grades of quality

CODEX Standard (http://www.codexalimentarius.net)
Quality factors in the CODEX Standard for dates include the following: (1) dates should possess the characteristic colour and flavour for the variety, be at the proper

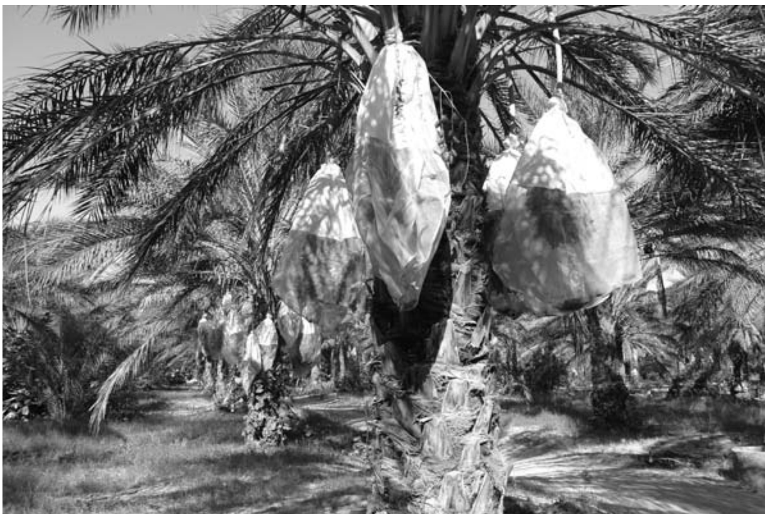

Fig. 4.3 Protective covers for date bunches.

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stage of ripeness and be free of live insects and insect eggs and mites; (2) moisture content of 26 to 30%, depending on the variety; (3) minimum fruit size of 4.75 g (unpitted) or 4.0 g (pitted); (4) absence of defects, including blemishes, mechanical damage, unripe, unpollinated, embedded dirt or sand, damaged by insects and/or mites, souring, mould, and decay. Dates and their products should be free from objectionable matter and microorganisms that represent a hazard to human health. The CODEX Standard for dates includes three sizes based on the number of dates per 500 g: small (>110 dates without seeds or >90 dates with seeds), medium (90–110 dates without seeds or 80–90 dates with seeds), and large (<90 date without seeds or <80 dates with seeds).

US standards

In the US standards for grades of dates, the quality score includes 20 points for colour, 10 points for uniformity of size, 30 points for absence of defects, and 40 for character (well developed, well fleshed, and soft). US Grade A or US Fancy are given to whole or pitted dates of one cultivar that achieve a score of 90 or higher. Lesser grades include US Grade B or US Choice, and US Grade C or US Standard. Defects that reduce the quality score include discolouration, broken skin, deformity, decay, puffiness, scars, sunburn, insect injury, improper hydrating, mechanical injury, lack of pollination, blacknose, side spot, black scald, improper ripening, souring, mould, dirt, and insect infestation (USDA, 1955).

In the US, Medjool date growers use a grading standard that differentiates four grades based on fruit size and freedom from defects as follows:

Grade	Dates per kilogram	Description
Jumbo	35–42	No blemishes, skin separation, or dryness
Large	44–51	No blemishes, skin separation, or dryness
Extra Fancy	44–53	Minor blemishes, packed all sizes together
Fancy	44–57	Some dryness and skin separation, packed all sizes together

4.6 Preharvest factors affecting postharvest fruit quality

Date cultivars vary greatly in quality at harvest and during postharvest handling. A large number of date palm trees in many countries are grown from seeds and most of these trees produce low quality dates that end up as animal feed or waste. Improvement of date quality and value (marketability) can be achieved by selecting a few (no more than ten) cultivars of good quality that meet consumer preferences and by limiting future plantings to these cultivars, while gradually replacing the poor quality cultivars with the selected good quality cultivars in each date-producing country (Kader and Hussein, 2009).

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Cultural practices (including irrigation and fertilization, pest management, fruit thinning, and harvest maturity) and climatic conditions (temperature, RH, rainfall, wind) influence the rate of development and quality at harvest of dates. For example, suboptimal water supply to the palm tree reduces yield and quality of the dates. Managing the crop load by reducing the number of bunches on the date palm tree and fruit thinning improves fruit quality (Ait-Oubahou and Yahia, 1999).

Only about 30–40% of the fruit normally ripen on the tree. Bunch bagging of dates on the tree with black or blue polyethylene, white agrisafe (polyethylene fleece) or paper bags significantly increases the rate of fruit ripening and increases rutab yield per bunch (Awad, 2007). Black and blue polyethylene bags were the most effective followed by agrisafe and paper bags.

4.7 Postharvest handling factors affecting quality

Postharvest losses in quality and quantity of dates are high and are related to incidence of physical, physiological and pathological disorders and to insect infestation (Ait-Oubahou and Yahia, 1999; Yahia, 2004). These losses are affected by moisture content of the dates, storage temperature and relative humidity, sanitation procedures, and efficacy of insect control treatments. Cooling dates soon after harvest to 10°C or lower and maintaining the cold chain throughout the postharvest handling steps are critical to reducing losses in quality and quantity (Yahia, 2004). An appropriate RH range for dates is 65–75%; at higher RH, dates will absorb moisture from the room air unless they are packaged in moisture-proof containers. Water activity of 0.65 to 0.85 corresponds with moisture content of 15 to 35% in dates. The lower the water activity, the greater the resistance to molds, yeast and bacteria that attack date fruits (Ait-Oubahou and Yahia, 1999; Yahia, 2004).

4.8 Physiological disorders

Several physiological disorders can affect dates, significantly influencing their quality in the market.

4.8.1 Darkening

Both enzymatic and non-enzymatic browning occurs in dates and increases with higher moisture content and higher temperatures (Yahia, 2004). Enzymatic browning can be inhibited at low oxygen concentrations and low temperatures.

4.8.2 Skin separation (puffiness)

Skin separation occurs when the skin becomes dry, hard and brittle, and separates from the flesh (Ait-Oubahou and Yahia, 1999). It is said to be severe when the

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skin separates from the flesh in a balloon-like fashion. This disorder develops during ripening of soft date cultivars, which vary in susceptibility. High temperature and high humidity at a stage before the beginning of ripening may predispose the dates to skin separation. Puffiness or sunken separation, caused by high temperature and/or high humidity before the beginning of ripening, may increase during curing and affects only soft cultivars.

4.8.3 Sugar spotting (sugaring)

Sugar spotting is characterized by the appearance of light-coloured spots under the skin and in the flesh and occurs mainly in soft date cultivars (also known as invert sugar dates) in which glucose and fructose are the main sugars (Ait-Oubahou and Yahia, 1999; Yahia, 2004). Almost all dry cultivars and several of the semi-dry cultivars contain large amounts of sucrose and are less sensitive to sugar spotting. Although it does not influence taste it alters fruit texture and appearance. Incidence and severity of sugar spotting increases with storage temperature and time. Sugar spotting decreases as the temperature decreases and when the moisture content falls below 22%, so storage at recommended temperatures minimizes this disorder. Sugaring may be reduced by gentle heating of the affected dates, but can reappear if unfavourable conditions prevail (Rygg, 1975). In Deglet Noor, sugar crystals may form within the flesh when the dates become old.

4.8.4 Internal breakdown

Due to their high moisture content, soft date cultivars are susceptible to a physiological disorder known as internal breakdown which causes black discolouration of fruits, if they are not stored at the correct temperature (Ait-Oubahou and Yahia, 1999).

4.8.5 Black nose

Black nose (fruit checking at the tip region of the fruit that turns a dark colour) is caused by high humidity as the fruit advances from the khalal to rutab stage of maturity (Ait-Oubahou and Yahia, 1999). This physiological disorder occurs particularly in Deglet Noor dates.

4.8.6 White nose

White nose is believed to be due to low RH as the fruit is advanced from the rutab to the tamr stage, especially in the case of Hillawi and Zahdi dates (Ait-Oubahou and Yahia, 1999). It is characterized by the presence of a discoloured ring near the calyx area, which sometimes covers 50% of the fruit. It has been suggested that dry winds for many days during the rutab stage of ripening can cause the basal region of the fruit to ripen more than the rest, causing the ring appearance. However, some

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studies have shown that this physiological disorder may be due to calcium within the fruit with the basal end containing less calcium than the apical end (Ibrahim, 1995). The disorder is alleviated or reduced in Hillawi dates by soaking in hot water (75°C) for five minutes (Ait-Oubahou and Yahia, 1999).

4.8.7 Mixed green

Mixed green is characterized by green spots on the ripe fruit, and can be alleviated by the application of some enzyme preparations (such as Pectino-42) (Ait-Oubahou and Yahia, 1999).

4.8.8 Splitting

Splitting can be a problem especially at the khalal stage. It can be caused by different climatic conditions (Yahia, 2004). Over-hydration, caused by a sudden increase in humidity, such as unseasonal rain, can give rise to a change in turgor pressure inside the fruit, resulting in splitting. Some date cultivars such as Deglet Noor are particularly susceptible to this disorder, whereas others such as Hillawi and Zahdi are less susceptible.

4.9 Pathological disorders

The most common pathological disorders causing quality deterioration of dates are fermentation by yeasts (the most significant problem) and fungal infection.

4.9.1 Souring

Yeasts which are found on dates are those capable of growing in relatively concentrated sugar solutions such as *Zygosaccharomyces* and *Hansenula* (Ait-Oubahou and Yahia, 1999). The formation of gas pockets under the skin, white aggregates of yeast cells, discoloured flesh and an alcoholic odour characterize the infected dates. Acetobacter bacteria may also convert the alcohol into acetic acid (vinegar). Souring of dates is due to the accumulation of ethanol and/or acetic acid. Dates are subject to fermentation and subsequent souring at the rutab and tamr stages, especially in soft cultivars, if not stored at the correct low temperatures. Souring can occur in dates with moisture contents above 25% when kept at temperatures above 20°C. Its severity increases with duration and temperature of storage. Storage at low temperatures reduces the incidence and severity of souring (Yahia, 2004).

4.9.2 Fungi

Fungi that commonly attack dates include *Aspergillus* sp., *Alternaria* sp., *Stemphylium botryosum*, *Cladosporium* sp., *Macrosporium* sp., *Citromyces ramosus*, *Phomopsis diospyri* and *Penicillium*. These fungi may cause significant losses before or just after

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harvest during rainy or high humidity periods and can attack fruits at the khalal or rutab stages (Djerbi, 1996). Fruit rot (*Rhizopus nigricans* Ehr) is a minor disease of dates, causing more damage at the rutab, rather than at the tamr stages. Calyx-end fruit rot (*Aspergillus niger* Van Tiegh) is a disease that causes losses at the khalal, rutab and tamr stages in conditions of high humidity. Black rot (*Botryodiplodia theobromae* Pat) postharvest disease has been reported on stored dates (Ait-Oubahou and Yahia, 1999). Dates with ≤ 23% moisture content are considered mostly safe from microbiological spoilage, but they become increasingly susceptible as their moisture content increases. *Catenularia fuliginea* Saito is able to grow on dried dates.

The proliferation of toxigenic strains of *Aspergillus parasiticus* and the production of aflatoxins (in excess of 300 mg g^{-1} at the khalal stage) during fungal growth at 28°C for 10 days has been observed in eight date cultivars (Ahmed *et al.*, 1997). Marked differences in susceptibility to infection and/or aflatoxin production have been observed between the different cultivars and/or stage of maturation. It has been concluded that toxigenic *A. parasiticus* could proliferate on any date fruit that had suffered mechanical damage, and therefore such fruits should be considered unsafe for human or animal consumption.

4.9.3 Disease control strategies

The high sugar content of date fruit, especially at the tamr stage, is helpful in reducing or avoiding the growth of some microorganisms, but microbial spoilage can still be a problem if soft cultivars of dates are not stored at the correct temperature and RH (Rygg, 1975; Khatri, 1997). Although a number of treatments have been used to control microbial decay, such as the use of ethylene oxide and pasteurization, such measures are not a substitute for cold storage. Steam-hydrated dates are more resistant to attack by microorganisms than natural or non-hydrated dates because of the partial sterilization of steam-dehydrated fruits.

Some of the strategies proposed by Kader and Hussein (2009) to reduce disease problems are:

- Drying the dates to 20% moisture or lower to greatly reduce incidence of molds and yeasts.
- Maintaining recommended temperature and RH ranges throughout the handling system.
- Avoiding fluctuations in temperature to prevent moisture condensation on the dates, which may encourage growth of decay-causing microorganisms.
- Using adequate sanitation procedures in the packinghouse and storage rooms to reduce potential sources of microbial contamination.

4.10 Insect pests and their control

4.10.1 Insect pests

Several insects can cause serious damage to dates at different developmental stages (Carpenter and Elmer, 1978; Dowson, 1982; Ait-Oubahou and Yahia, 1999).

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Oligonychus afrasiaticus McGregor and *O. pratensis* Banks are mites that cause a disorder known as 'Bou Faroua' disorder, which affects fruit at the hababouk stage. The larvae develop around the fruit producing a white filament netting, which in turn causes fruits to drop prematurely. Infestation with the date stone beetle (*Coccotrypes dactyliperda*) has the same consequences, with the fruit dropping at the immature green stage. *Parlatoria blanchardii* attacks the fruit while still green and forms white filaments around the fruit, which reduce respiration and photosynthesis and the fruit do not reach maturity. The date or carob moth (*Ectomyelois ceratoniae* Zeller) is another Lepidotera, which is a widely distributed pest in different date producing areas and is the cause of significant postharvest losses in stored dates. The moth is common on dates, pomegranates and carobs. Several other insects, such as *Batrachedra amydraula* Meyr, *Carpophilus hemipterus*, *C. mutilatus*, *Urophorus humeralis* and *Haptoncus luteolus*, can cause serious damage to dates on the bunch or after harvest. Other pests, including *Vespa orientalis*, *Cadra figulilella*, *Arenipses sabella* and the mushroom mite (*Tyrophagus lintneri* Osborn) can infest stored dates. The fig-moth (*Ephestia cautella* Walk.) is an important postharvest pest in some growing regions that can attack dates in the orchard, packinghouses or store (Ahmed, 1988). Dates at khimri, khalal and rutab stages are not attacked by this insect, only fruits at the tamr stage. The saw-toothed grain beetle (*Oryzaephilus surinamersis* L.) is a serious insect pest of stored dates in some regions.

4.10.2 Control methods

Fumigation by methyl bromide or phosphine, ionizing radiation, low and/or high temperatures and modified atmospheres can be used to control insects in dates (Paull and Armstrong, 1994; Yahia, 1998; 2004; 2009).

High temperatures

Heat treatment of dates at 60–70°C for two hours killed 100% of both the fig-moth and the saw-toothed beetle, but resulted in a shiny appearance or glazing of the fruit (Hussain, 1974). Exposing dates to temperatures of 65–80°C for 30 min to 4 h at high humidity controls insects (Yahia, 2004), but this approach is not always very efficient for controlling insects in dates with high moisture content, as such high temperatures for prolonged periods may cause darkening and the appearance of a dull colour and loss of flavour. Heated air at 50 to 55°C for 2 to 4 hours (from the time the fruit temperature reaches 50°C or higher) is effective for insect disinfestation (Navarro, 2006), but once again use of higher temperatures is not recommended because it makes the colour of the dates darker. Hussein *et al.* (1989) reported that boiled water is more efficient at controlling insect infestation of dates than exposure to air at 70°C. Very hot water increases sugar loss which can reach up to 20%.

Low temperatures

Low temperatures can significantly reduce insect infestation (Yahia, 2004). Temperatures below 13°C will prevent feeding damage and reproduction, and

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temperatures of 5°C or lower are effective in controlling different forms of insect (Barreveld, 1993). Fig-moth larvae may live for 85 days at 2–6°C, but storage at 0°C can result in total mortality of the larva of the fig-moth and the adult grain beetle after 15 and 27 days, respectively (Hussain, 1974). Packed fumigated dates may be kept free of infestation at 4°C for as long as one year (Hussain, 1974). Freezing at −18°C or lower for at least 48 hours (from the time when the fruit temperature reaches −18°C or lower) is enough to kill all life stages of insects in stored products. This treatment is used by handlers who market organic dates.

Ionizing radiation

Ionizing radiation at doses below 1 kGy (the currently approved limit for use in fruits and vegetables) has potential for effective insect disinfestations without negative effects on the quality of dates (Ahmed, 1981; Al-Taweel *et al.*, 1993). Ahmed *et al.* (1982) found that an irradiation dose of 0.86 kGy was adequate for the disinfestation of polyethylene wrapped small date packages, causing complete inhibition of adult emergence in both *Ephestia* and *Oryzaephilus*. Al-Taweel *et al.* (1990) reported that an irradiation dose of 0.44 kGy for 30 minutes was sufficient to disinfest dates and no live insects could be detected after a storage period of 185 days. Azelmat *et al.* (2005) found that 0.3 kGy was the minimum needed to prevent damage from feeding and prevent adult emergence and 0.45 kGy was required to kill the fourth instar of *Plodia interpunctella* (Huber) (Lepidoptera: Pyralidae).

Fumigation

Methyl bromide at 30 g cubic metre^{-1} (30 ppm) for 12 to 24 hours at temperatures above 16°C is very effective for insect disinfestation (Ait-Oubahou and Yahia, 1999). Although methyl bromide for many applications may be phased out, its use for postharvest insect disinfestation is likely to be continued as long as it is trapped and reused. However, it is a good idea to research alternatives in case the use of methyl bromide is not permitted in the future. A potential substitute for methyl bromide is sulphuryl fluoride at 34 g cubic metre^{-1} for 24 hours at 20–25°C, which has recently been registered by the United States Environmental Protection Agency (USEPA); however, environmental groups are also campaigning against this compound due to its potential negative effects on the environment. Phosphine is an effective fumigant, but treatment with phosphine takes 3 to 5 days at 20°C and 60% RH. However, using phosphine as a gas can shorten the required treatment time to a few hours. Current regulations in individual countries should be consulted before these fumigants are used. Fumigation was found to be more efficient when applied under low pressure. Ahmed *et al.* (1982) compared methyl bromide fumigation and irradiation of Zahdi dates and reported that both techniques are efficient for disinfestation during the first period of storage (25 days), but reinfestation of dates occurred during storage leading to detection of live insects. Thus, disinfested dates must be protected from reinfestation by storage at low temperatures and in insect-proof packages.

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Modified atmospheres (MA) and controlled atmospheres (CA)
Storage in N_2 or 100% CO_2 can control insects for 1–2 days at ambient temperature, and low O_2 atmosphere can also inhibit enzymatic browning (Navarro *et al.*, 1998; Yahia, 2009). Packing infested dates in polyethylene bags with 80–90% vacuum resulted in 100% mortality after two days (Hussain, 1974).

Biological control
Some biological methods for the control of the insect pests of stored dates, such as sterile insect technique, cytoplasmic incompatibility and the use of parasites, have been tried (Ahmed, 1988; Ahmed *et al.*, 1982; 1994), but none of these methods are used commercially. Organic dates may be treated with 100% carbon dioxide for 2 days since chemical fumigants such as methyl bromide cannot be used. Heat treatments or freezing can also be used for insect disinfestation of organic dates.

4.11 Postharvest handling practices

4.11.1 Harvesting

As mentioned above, the stage of maturity at which dates are harvested depends on the cultivar and the purpose and intended day of fruit consumption. Time of harvest can be based on the date fruit's appearance and texture (related to moisture and sugar content) (Yahia, 2004). Proper timing of harvest reduces incidence and severity of cracking or splitting of dates, excessive dehydration, insect infestation, and attack by microorganisms. Dates are harvested in July to August at the khalal stage or in September to December at the rutab and tamr stages in northern hemisphere production regions. The time taken for fruit to ripen depends on the cultivar, the heat units received during the growing season and the stage at which the fruit are picked. For early ripening cultivars the fruit within the bunch may take as long as 3–4 weeks to complete ripening, while for late ripening cultivars, fruit within the bunch ripens in about 8–12 weeks. Early harvest is commonly practiced to take advantage of higher prices in the market and to avoid adverse weather conditions, cracking or splitting of fruits, excessive dehydration in early maturing fruits, insect infestation, and microorganism attack.

As ripening of dates is progressive on the bunch some fruits can be overripe while others are still at the khalal or rutab stages. Selective picking of individual dates or strands is often practiced for good quality at prime maturity. When this approach is adopted, a number of pickings are made before harvesting all fruits. Frequency of picking depends on several factors such as type of date (soft, dry or semi-dry), climatic conditions, market demands, handling methods, cost of handling and availability and cost of pickers. On average, however, when ripe fruit are picked from bunches, three pickings are required over several days. The common method, though, is to harvest by bunch when the majority of dates are ripe. Yellow khalal Barhee (Plate VI) dates are sometimes marketed on branches (strands) or bunches (Fig. 4.4). The whole bunches are harvested when the dates

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Fig. 4.4 Roadside selling of dates in southern Tunisia.

are fully yellow and lowered to ground level, then hung on a carrier for transportation to the packinghouse or to the market. Green to greenish-yellow and ripe (rutab) fruits are removed from the branches before packing for shipment to markets. Rutab and tamr dates are commonly harvested as whole bunches (Fig. 4.5) when the majority of dates are ripe, which are lowered to ground level and shaken into a bin to remove the ripe dates. Defective dates can also be removed from bunches (Plate VII in the colour section between pages 274 and 275) and strands (Fig. 4.6). The fruit are then packed in bulk bins and sent to the packinghouse. Date bunches on the tree are usually covered with net covers to collect the fallen ripe fruits. Fallen dates on the ground, which are more subject to mechanical damage, should never be collected and sold for human consumption because of the increased chance of microbial contamination and embedding of soil into the flesh when the dates touch the ground (Kader and Hussein, 2009).

As the palm tree grows taller, harvesting the dates by hand becomes more difficult and more costly as the trees have to be climbed. A wide belt woven out of coir is often used to support the climber's back; the climber then cuts off the whole bunch. Hand-harvesting of dates in the USA involves the use of aluminum

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Fig. 4.5 Harvesting dates.

Fig. 4.6 Removing defective dates from strands.

ladders for short palms and picking platforms for taller palms. Pickers use different types of container and harvesting aids to lower the dates from the palm to ground level. If picking individual fruit, the picker empties the container (baskets, bags or buckets) and climbs the palm again until all fruits at the same stage are harvested. Bunches may be lowered either by ropes or by passing the bunch hand-to-hand.

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Fruits are also harvested by shaking the bunch and all mature fruits which detach easily drop onto mats spread on the ground around the palm. Very soft fruits can be damaged in this process.

The cost of hand harvesting (Fig. 4.5) can reach as much as 45% of the operational costs, and therefore efforts have been made to develop mechanical harvesting methods for dates (Ibrahim *et al.*, 2007). Some trials have been carried out on Deglet Noor dates in the Coachella valley, California, using platforms built on an extensible tower, enabling the picker to move from one palm to the other (Brown, 1982). More recently, the concept of mechanical harvesting of mature fruit bunches has been developed, in which whole bunches are cut off on two harvest dates as the majority of the fruit per bunch reach the tamr stage. A later development has been the use of mechanical shakers, in which the fruit bunch axis is shaken and fruit collected under the tree. Mechanical harvesting has been found to reduce the cost of harvesting operations and consequently, the mechanical harvesting method that involves cutting off the whole fruit bunches and then using mechanical shakers to remove the fruit has become the standard procedure in the Coachella valley. A still more recent development has been the use of a hydraulic crane with a basket built onto a truck, which is used by the picker to reach the top of the tree. The picker cuts off the whole bunch and places it in the basket, which is lowered by the crane to a shaker-trailer for shaking. Shaking makes the fruit fall into the bulk bins placed beneath the shaker-trailer. The bulk bins are then lifted by a shuffle and placed in trucks to be transported to the packinghouse. Almost 80% of dates produced in USA are now harvested by this method, which has cut harvesting costs by 50% (Rygg, 1975; Brown, 1982; Hodel and Johnson, 2007). Outside the USA, mechanical aids for harvesting have been used extensively in Saudi Arabia (Alhamdan, 2006) and the United Arab Emirates. Dry types are more suited for mechanical harvesting as the softer types of date can be damaged by inappropriate harvesting.

4.11.2 Ripening

Dates may need to be ripened after harvest when picked early to avoid damage by rain, insects or other factors (Yahia, 2004). Ripening rooms should be equipped with the means to control temperature and humidity and should have adequate air circulation. The exact temperature and time required for ripening depends on the type of date, stage of maturation and condition at harvest. A temperature of 40–43°C is recommended for ripening Khadrawy, Kustawy, Hayani, Sayer, Khalasa and Sphinx dates (Hyde, 1948). Temperatures of 45–46°C and 70% RH for a period of 2–4 days or longer are required to ripen cultivars with thick flesh such as Iteema, Maktoom and Saidy. Deglet Noor dates should not be ripened at temperatures above 35°C, in order to avoid fruit darkening and loss of flavour. Soft cultivars such as Hallawi, Dayri and Zahdi can be ripened at slightly higher temperatures (35–38°C). Ripening of these cultivars is complete in about 2 to 4 days when they have lost their translucency and little or no hard tissue remains.

Other techniques and chemicals have been tested for ripening dates. Dipping fruits of cv. Khasab, widely grown in Saudi Arabia, in 1% NaCl plus 2% acetic acid

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resulted in good quality fruits after ripening (Asif and Al-Taher, 1983). Ripening enhancement of khalal stage dates can be achieved by treatment with acetic acid, ethanol, or acetaldehyde. In North African countries, where the weather is hot and the air is sufficiently dry, harvested immature fruits are ripened outdoors in the sun or in shade. Fruits are separated individually and spread on the ground or kept on the bunch where they ripen progressively. Although this technique is simple and cheap, the exposed fruits are subjected to adverse conditions such as rain, dust from winds, bird attack, rodents, etc., and ripening conditions cannot be controlled. Freezing for at least 24 hours can be used to accelerate ripening of khalal dates to rutab stage. Freezing at −35°C to −50°C, which causes less damage to the tissues, is better than freezing at −15°C to −18°C, which causes some damage to cell membranes and walls (Kader and Hussein, 2009).

4.11.3 Dehydration

Dehydration aims to achieve an appropriate sugar:water ratio which should be close to 2 for soft dates, greater than 2 for dry dates and lower than 2 for very soft dates. This ratio is a good indicator of date quality behaviour in storage. Fruits of soft and semi-dry cultivars need to be dehydrated to eliminate excess humidity if they are not to be consumed immediately or are to be stored at very low temperatures (Rygg, 1975). The temperature and duration required to reduce water content depend on the type of date, use and flesh consistency. Dates are either kept in bunches or separated from the bunch for dehydration. In countries with low air humidity, dates are spread out on trays and then exposed to the sun or under plastic tunnels until the moisture content has reduced to the desired level. Sometimes dehydration is carried out simultaneously with ripening until a safer level of moisture content is reached. This process is commonly accomplished by recirculating ambient air until high humidity builds up and then introducing fresh preheated air at very low humidity. For this process, the dates can be spread on stacked trays within a pallet that is covered by a shrink film with ventilation openings at the top and bottom of the pallet, or it can be carried out within plastic greenhouses with good air circulation. Drying in plastic houses, which can be constructed at a reasonable cost, protects the dates from dust, birds, rodents and other damaging factors. If solar or ambient-air drying is not possible, heated air can be used to dry the dates to their desired moisture content. The temperature of heated air used for drying depends on the cultivar, as indicated in the ripening section. Over-drying to less than 20% moisture should be avoided to keep the dates soft. The desired moisture content is 23 to 25%.

4.11.4 Hydration

If picked ripe and not over-dried, dates do not require hydration. However, sometimes hydration is used to soften the texture of some hard-type date cultivars. It is achieved by dipping dates in hot or cold water for a certain period of time. Dates are dipped in hot water or exposed to steam at 60 to 65°C and 100% RH for

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4 to 8 hours (Ait-Oubahou and Yahia, 1999). Steaming for 10 minutes is enough for some cultivars such as 'Fardh'. Hydration changes the dried dates into plump and glossy dates. Forced air circulation is used to improve uniformity of temperature and RH throughout the hydration room. In addition, this treatment is effective in controlling some microorganisms and improving the keeping quality of the fruit. A treatment commonly used in California for Deglet Noor dates consists of introducing steam at 5 psi until the temperature reaches 60°C for 4–8 h. In Algeria, the treatment consists of a temperature of 65–70°C and 55% RH for 24 h (Rygg, 1971). High acidity dates are difficult to soften by hydration, and acidity during the process changes very little unless neutralizing agents are added. The addition of alkaline ammonium sulphite during hydration improves the quality of hydrated dates that are characterized by moderately high acidity (Rygg, 1975).

4.11.5 Pasteurization

Dates may be pasteurized by exposure to 72°C and 100% RH air until their flesh temperature reaches 66°C, where it is kept for one hour. However, such conditions may induce colour darkening of the dates.

4.11.6 Preparation for market

Cleaning

In general, and despite the necessary precautions taken during harvesting and transport, dates arriving from the farm may be comtaminated with particles of dirt and dust, sand particles, plant debris and chemical products. Dates should be cleaned to remove these particles which stick to the date skin. Cleaning can be achieved by (i) blowing air on the fruits and brushing the dates softly to avoid damage to the fruit skin or by (ii) washing the fruits with running water. Dates can also be cleaned by passing them over damp towelling or with the use of washers. Spray jets can be used for soft dates instead of washers. Germicides are used to reduce microbial activity, and moist dates are air-dried after washing to remove excess water before packaging.

Sorting

Dates are sorted to remove culls and to separate them into uniform sizes. Sorting can be carried out manually or mechanically in crates or on moving belts. Dates can be sorted according to maturity, flesh consistency, colour, shape and size. Within different groups, dates are separated according to quality. Discarded fruits consist of dates with defects and abnormalities such as parthenocarpic fruits, immature or overripe fruits, fruits mechanically damaged during harvesting or on the palm, fruits damaged by birds or insects, and fruits with physiological disorders or diseases.

Sizing

This operation is done manually or mechanically to separate dates based on their size and weight. Uniformity of size in a package is one of the quality criteria for

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dates. Date size varies depending on the cultivar. Medjool dates in the USA are classified into three size categories: Jumbo for less than 10 dates per pound, Mixed for 10 to 15 dates per pound and Conventional grade for more than 15 individual dates per pound.

Surface coating
The objective of this process is to reduce stickiness and improve appearance. Several materials have been recommended for this purpose including a 5% or 6% solution of soluble starch as a dip, 3% methyl cellulose or a combination of 2% butylated hydroxyanisole, 2% butylated hydroxytoluene, 6% vegetable oil, 90% water and a wetting agent.

Packaging
Dates are packed in several types and sizes of packages (Plate VI and Fig. 4.7 and 4.8). Some dates are marketed in 15-pound flats of fibreboard or wood, others in 5- or 10-pound cartons. Large reinforced cartons are used for packing dry dates, especially for export. Consumer packages in a number of sizes and shapes are widely used for dates (Fig. 4.7 and 4.8). They include transparent film bags and trays overwrapped with film. Round fibreboard cans with metal tops and bases containing 500–1000 g are also used. Rigid transparent plastic containers with a capacity of 200–300 g are commonly used. Small consumer packages are also used such as bags containing about 50–60 g.

Cooling
Cooling to below 10°C (preferably to 0°C) before transportation or storage under the same temperatures (0°C to 10°C) and 65–75% relative humidity is important

Fig. 4.7 Packaged dates.

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Fig. 4.8 Consumer packages of 'Deglet Noor' dates.

to maintain quality. Hydrocooling can be used to cool khalal dates to near 0°C in 10 to 20 minutes, depending on initial temperature (Elansari, 2008), but requires effective disinfection of the water and removal of excess surface moisture from the cooled dates before packing in the shipping containers. Use of a perforated plastic liner within the box can reduce water loss during transportation and marketing.

4.11.7 Storage conditions

Low temperature storage is the most effective method of maintaining high quality in dates (Rygg, 1975; Benjamin *et al.*, 1976; Ait-Oubahou and Yahia, 1999; Yahia, 2004). It minimizes loss of colour, flavour and textural quality, delays development of sugar spotting, incidence of moulds and yeasts, and insect infestation, and prevents development of syrupiness (due to conversion of sucrose into reducing sugars) and souring of excessively moist dates. Studies on the cold storage of dates were carried out in the United States as early as 1916. Those early studies indicated that freshly picked dates could be successfully stored for 5 months at 1–2°C (Rygg, 1975; Nixon and Carpenter, 1978). However, it was later demonstrated that date fruits must be dehydrated to remove excess moisture if successful storage is required both at room temperature and under refrigeration. In general, soft date cultivars require a lower relative humidity in the store compared to semi-dry cultivars (Rygg, 1975). The effect of different temperatures on the storage behaviour of Deglet Noor dates was investigated by Rygg (1948; 1956). Fruit of this cultivar could be stored for one year with little loss in quality at 0°C, for 8 months 4.4°C, for 3 months at 8°C, and for one month at 12°C. Deglet Noor dates with moisture content of 28 and 24% could be stored at 4.4°C for 3 and 12 months, respectively (Rygg, 1948).

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Dates picked at the khalal stage should be stored at 0°C and 85 to 95% RH to reduce water loss, delay ripening to the rutab stage and maintain their textural quality and flavour. Packaging in plastic bags or use of a plastic liner in the box helps in reducing water loss. Date fruits at the rutab stage are highly perishable and require immediate refrigeration (Abdul-Latif, 1988). Optimal temperature for tamr dates is 0°C for 6–12 months, depending on the cultivar (semi-soft dates, such as Deglet Noor and Halawi have longer storage life than soft dates, such as Medjool and Barhee). For longer storage durations, use temperatures below the highest freezing temperature of −15.7°C. Dates with 20% moisture or lower can be kept at −18°C for more than one year, or at 0°C for one year, or at 4°C for 8 months, or at 20°C for one month; relative humidity should be kept between 65 and 75% in all cases (Yahia, 2004). Ripe dates at the rutab or tamr stages, commonly harvested and handled in the world market, are not sensitive to chilling and freezing temperatures. However, freezing temperatures can injure dates at the early stages of khimri and khalal.

Relative humidity also has a profound effect on the date's quality. Pathological and physiological deterioration increases with increasing moisture content and storage temperature (Rygg *et al.*, 1953). Very soft and syrupy dates are subject to mould invasion and fermentation more than other types of dates. Relatively small differences in moisture content may have an important effect on the keeping quality of Deglet Noor fruits (Dull *et al.*, 1991). At 24°C, the rate of skin darkening is four times faster in Deglet Noor dates stored at 24% moisture content than at 20% moisture content (Rygg, 1975). Relative humidity during storage should be controlled according to fruit initial moisture content to avoid excess drying or gaining of moisture. Generally, 75% RH or lower is recommended for fresh dates in storage. At high RH, dates will absorb moisture from the air unless they are packaged in moisture-proof containers.

Dates can readily absorb odours and thus should not be mixed in storage or during long distance transport with garlic, apples, onions or potatoes or other foods with strong odours (Yahia, 2004; Ait-Oubahou and Yahia, 1999).

4.11.8 Handling organic dates

The main concern when handling and storing organic dates is to keep them separate from conventionally produced dates and other produce items and to prevent any possibility of cross-contamination of the organic produce by chemical residues that may be present on the conventionally produced fruit. Thus, it is best to use a separate storage room for the organic produce. If this is not feasible, then a physical and spatial separation of at least one metre should be maintained between the organic and conventional produce when stored in the same room. If the produce is well protected from cross-contamination by packaging, the potential for cross-contamination is much reduced (Kader and Hussein, 2009).

The storage room must be thoroughly cleaned to remove any possible residues from previously stored, conventionally produced foods. It is important to keep accurate, specific records of cleaning and sanitizing materials identified by brand

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name and source. A list of permitted cleaners, disinfectants, sanitizers, and other chemicals is available on the website of the Organic Materials Review Institute (http://www.omri.org). The area for food storage must be physically separate from non-foods, especially materials which can contaminate foods by odours or spillage. Packaged organic products must be received into, and despatched from, storage facilities unopened, free from damage and correctly labelled. The optimal storage conditions (temperature and relative humidity) are the same for organic and conventional dates. The potential storage life for organic dates may be shorter than for conventional dates if the latter are treated with approved chemicals to control decay and/or insects.

4.12 Processing

Various products can be obtained from dates (Al-Abid *et al.*, 2007a, b; Barreveld, 1993). Dates are marketed whole, pitted, cut into small pieces or macerated (ground or chopped). Whole unpitted or pitted dates may be marketed loose or pressed (compressed into layers using mechanical force). Dates can be pitted and stuffed and used in pastries. Date flour can be obtained from dry or dried dates. Syrup can be produced from very soft dates (drained out) or from low quality dates after hydration and maceration. The syrup obtained is concentrated to 30/35°Brix then filtered to reach a light brown colour. Sugar is extracted from dates, and vinegar, alcohol and yeast can also be produced from dates (Munier, 1965; Al-Abid, 2006; Sidhu, 2006). Kimri stage (green) dates may be used to make pickles and chutney. Khalal stage dates may be used for jam or dates-in-syrup. Rutab stage dates may be used for jam, butter, date bars and date paste. Tamar stage dates may be processed into date bars, date paste, date syrup or concentrated Tamr juice (Dibis). Date processing by-products and low quality dates may be used for sugar extraction or production of sugar alcohols, citric acid, ethanol, vinegar or baker's yeast.

4.13 Food safety considerations

Safety factors in dates include contaminants such as mycotoxins, bacterial toxins, heavy metals (cadmium, lead, mercury), environmental pollutants, residues of pesticides and microbial pathogens (Al-Turki and Magid, 2004; Yahia, 2004). While health authorities and scientists regard microbial contamination as the number one safety concern, many consumers rank pesticide residues as the most important safety issue. Unless fertilized with animal and/or human waste or irrigated with water containing such waste, dates normally should be free of most human and animal enteric pathogens, unless they have been contaminated if allowed to fall to the ground. Organic fertilizers, such as chicken manure, should be sterilized before use in date orchards to avoid the risk of contaminating dates that come into contact with the soil with *Salmonella, Listeria* and other pathogens.

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Dates should not be picked from the ground and used for human consumption because of the greater risk of contamination with human pathogens. Strict adherence to 'Good Agricultural Practices' during production, 'Good Hygienic Practices' during post-harvest handling, and 'Good Manufacturing Practices' during processing are strongly recommended to minimize microbial contamination (Kader and Hussein, 2009).

Sanitation standard operating procedures (SSOPs) are specific procedures that allow the date processing plant to achieve sanitary process control in its daily operations. These procedures include:

- safety and purity of the water used in all operations
- cleanliness of utensils and equipment
- prevention of cross-contamination
- hand washing and toilet facilities
- protection of food from contaminants
- labelling and storage of toxic compounds
- monitoring employee health and not allowing sick employees to touch the food
- pest control.

Proper washing of dates significantly reduces the microbial load on their surfaces. Clean, disinfected water is required in order to minimize the potential transmission of pathogens from water to dates, from infected to healthy dates within a single lot, and from one lot to another over time. Waterborne microorganisms, including postharvest plant pathogens and agents of human illness, can be rapidly acquired and taken up on date surfaces. Natural date fruit surface contours, natural openings, harvest wounds and scuffing can be points of entry as well as providing a safe harbour for microbes. In these protected sites, microbes are largely unaffected by common or permitted doses of postharvest water sanitizing treatments, such as chlorine compounds, ozone, peroxyacetic acid and hydrogen peroxide. It is essential, therefore, that an adequate concentration of sanitizer is maintained in water in order to kill microbes before they attach or become internalized in the dates. In some countries, standards of microbial quality have been established with a maximum microbial load allowed in any of the samples tested of 1000 CFU g^{-1} yeasts, 10 000 CFU g^{-1} moulds, and/or 10 CFU g^{-1} *E.coli.* Such microbial load testing may be helpful in indicating the efficacy of the sanitation procedures used to prevent microbial contamination.

4.14 Conclusions

Despite being an important food crop, only a small proportion of the world production of dates is handled in world trade. The reasons for this are diverse and include inadequate handling techniques used in several countries, and lack of information for small farmers who are the dominant producers. Research and reviews written on the postharvest physiology and handling of dates, particularly those written in recent years, are scarce. Topics which need investigating include

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selection of adequate cultivars for better quality fruits and smaller tree size, improvements of harvesting methods, ripening procedures, dehydration and hydration techniques, safe methods for insect and pathogen control, prevention of toxins and development of adequate detection methods, practical methods for moisture determination, optimal packaging and storage conditions, and further biochemical studies on sugar interactions, tissue softening and browning.

Some of the important means to produce good quality dates and to maintain quality after harvest include: selecting the right type of male clones for pollinating female cultivars, developing adequate date palm mechanization, especially for pollination and harvesting, proper use of the cold chain, adequate packaging and packages, adequate food safety measures, effective methods of insect control and prevention of reinfestation during postharvest handling. Storage and transport at low temperatures is the most important way of maintaining quality of dates because it minimizes loss of colour, flavour, and textural quality; delays development of sugar spotting, reduces incidence of molds and yeasts, and insect infestation; and prevents development of syrupiness (due to conversion of sucrose into reducing sugars) and souring of excessively moist dates.

4.15 References

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Plate V (Chapter 3) Harvesting dabai fruit by placing a net on the ground and climbing up the tree, then using a long pole with a sharp sickle at its end to harvest branches with fruits.

Plate VI (Chapter 4) Barhee (Barhi) dates.

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(a)

(b)

Plate VII (Chapter 4) Removing defective dates from bunches.

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5

Durian (*Durio zibethinus* Merr.)

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Abstract: Durian is one of the most important fruits grown in South-East Asia. It is named king of fruit due to its rich sweet creamy delicious taste with strong distinctive odor. This chapter includes discussion of its unique biology, surprising nutritional value, volatiles, factors affecting quality, complicated maturity indices, handling procedure, disorders, important pests and their control, processed products and potential medicinal uses.

Key words: *Durio zibethinus*, durian, postharvest biology, postharvest technology, processing.

5.1 Introduction

Durian got its fame from its delicious creamy taste with strong offensive odor and its spiny fruit. It is named 'King of fruit' in the countries where it is cultivated.

5.1.1 Origin, botany, morphology and structure

Durian is in the order Malvales, family Bombacaceae and genus *Durio*. There are six out of 29 species in this genus that are edible including *D. kutejensis*, *D. oxleyanus*, *D. graveolens*, *D. ducis*, *D. grandiflorus* and *D. zibethinus*. Durian is believed to originate from Borneo Island, where more *Durio* species have been found than anywhere else (Reksodihardjo, 1962; Siti Zainab and Zainal Abidin, 2008). Once a minor crop, durian is now an important tropical fruit crop in South-East Asia.

The fruit is a loculicidal capsule (Plates VIII A and IX A in the colour section between pages 274 and 275) with a round, ovoid, cylindroidal or ellipsoidal shape generally consisting of five segments (locules). The size ranges from 1–5 kg, with a large cylindrical stem, 1–1.2 cm in diameter. The stem consists of two parts (Plate VIII B). The lower part, from the fruit to the abscission zone, develops from

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a flower pedicel. The upper part, from the abscission zone to the attachment point on the branch, develops from the flower peduncle. The fruit drops off the tree at the abscission zone upon ripening.

The rind is brownish-green to yellowish-green on the outside, white on the inside, tough and fibrous, 0.3 to 1.5 cm thick and covered with three to seven sides of pyramidal sharp and hard spines. At the middle of each locule there is a suture running from the stem to the stylar end. This is the dehiscense zone where the ovary wall of each individual carpel joins the others, early on during flower development, forming the locules. It is where the fruit eventually splits or dehisces. Each locule consists of one to five pulp units, depending on the fertilization of the ovules, attached to the axis of the fruit. The cream coloured to dark yellow pulp (Plate VIII C) is the aril that develops from the funiculus of each seed, and expands outward covering the whole seed (Amad Tarmizi and Nanthachai, 1994; Bhusiri, 1981; Polprasid, 1983).

If pollination and fertilization is complete, the fruit will develop into a symmetrical shape, but if it is poorly pollinated and fertilized the fruit will have odd twisted shapes (Plate VIII A). The fruit forms from one flower, with only one ovary. Among 10–30 flowers on an inflorescence emerging from main branches, only one to three develops into mature fruit.

Two important structures of durian are often overlooked. One is the peltate trichome (Plate VIII D) on the surface of the spine. The second is the development of periderm and lenticel on the spine surface as well as along the groove between spines, especially along the suture, giving the brown color of the fruit when they become mature.

Seeds are large, 2–3 cm wide and 5–7 cm long, hard and covered with a thin light brown skin (testa) which turns brown when the fruit is mature. In most cases when the seed develops well, the aril around the seed is thin (2–10 mm). On the other hand, the seed may be aborted and then shrivels but the aril continues to grow and forms a relatively thick pulp, up to 3 cm. With the above mentioned structure of durian, each fruit contains 55–66% rind, 20–35% aril and 5–15% seeds (Polprasid, 1983).

5.1.2 Distribution, production area and trade value

Durian is a seasonal tropical fruit, available mainly between May and August. A minor crop may also be available in certain years during December and January. Early crops may be obtained as early as mid March and late crops may be available in October. With the use of plant growth regulators, particularly Paclobutrazol, durian is now available all year round in Thailand. Durian cultivation extends throughout South-East Asia, Sri Lanka, the southern part of India and Madagascar. Small scale cultivation is also found in the Northern Territory and Queensland, Australia. Production area and trade value is minimal there and not included in FAO statistics. However, statistical data from Thailand, Malaysia and Indonesia are shown in Table 5.1. Durian is now a major fruit crop exported from Thailand. It is popular among Asian communities including those in Australia, Europe and North America, although the main export market is China.

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Table 5.1 Durian production area and export volume in three leading producing countries

Country	1988		2003		2008	
	Production (Hectares)	Export (Tons)	Production (Hectares)	Export (Tons)	Production (Hectares)	Export (Tons)
Indonesia	36 054	–	53 770	13	47 600	32
Malaysia	48 049	19 889	116 270	26 236	96 762	19 485
Thailand	84 500	6 694	116 615	87 433	111 685	219 438

5.1.3 Uses of fresh and processed products, and nutritional value

Durian is mostly consumed as fresh fruit. Different preferences prevail among consumers in different countries. While those in Malaysia, Singapore and Indonesia prefer the fully ripe durian with a very soft texture and strong odor, the Thai mostly prefer just-ripe durians with a soft to firm texture and mild odor.

Two surveys conducted in Thailand showed that 27% of the population surveyed did not like and even hated durian due to its strong odor and its high calories, but almost 80% said they would consume durian if it had less odor (Tiyaratanakura, 1991; Uthairatanakij, 1991). The most popular cultivar is the Thai cultivar ‘Monthong’ that has a mild odor. Recently, the Thai Department of Agriculture released two durian hybrids, Chanthaburi 1 and 2, having a very mild odor, fine texture and early maturity (Somsri *et al.*, 2008). Other popular cultivars include Indonesian ‘Sitokong’, ‘Petruk’, ‘Sunan’, ‘Sukun’ and ‘Simas’; Malaysian ‘D2’, ‘D10’, ‘D24’ and ‘D99’ and Thai ‘Chanee’, ‘Kanyao’ and ‘Kradum’.

Durian aril is high in carbohydrate (10–30%) and fat (1–6%) depending on the cultivar and stage of maturation. Its nutritional value is shown in Tables 5.2 and 5.3 (Arancibia-Avila *et al.*, 2008; Charoensiri *et al.*, 2009; Haruenkit *et al.*, 2009; Toledo *et al.*, 2008). It is widely believed that durian has aphrodisiac properties, and that consumption of durian in conjunction with alcohol may lead to sickness or even death. However, these points have never been proven. The rind is boiled and used to treat skin ailments. The ash of the fruit wall is used for curing infant fever. The aril may be preserved in many forms, including frozen and fried, detailed in section 5.10, but the most popular preserved form is durian paste.

5.2 Fruit development and postharvest physiology

5.2.1 Fruit growth, development and maturation

Fruit growth begins after cross pollination by insects or bats, which takes place around an hour after sunset. The pattern of fruit development is simple sigmoid. The total period of development varies among cultivars, ranging from 90 to 150 days after anthesis. A comparative study between the growth of ‘Kradum’, a cultivar characterized by small fruit, that matures at around 90 days after anthesis (DAA), and ‘Monthong’, a large cultivar that matures at around 120 DAA, showed that during the first 14 days, both cultivars had a slow growth phase, followed by a

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Table 5.2 Nutritional composition of durian aril (per 100 g)

Component	Range
Moisture (g)	58.0–70.9
Calories(kcal)	134–147
Protein (g)	2.0–3.3
Fat (g)	1.2–4.3
Carbohydrate (g)	15.0–36.1
Fiber (g)	1.2–1.9
Ash (g)	0.8
Calcium (mg)	7.4–49
Phosphorous (mg)	27–56
Iron (mg)	0.1–2.0
Vitamin A (I.U.)	890
Thiamin (Vitamin B1) (mg)	0.10–1.08
Riboflavin (Vit B2) (mg)	0.11–0.28
Niacin (mg)	1.0–1.1
Ascorbic acid (mg)	20–62
Vitamin E (mg)	0.74–1.43

Table 5.3 Antioxidant capacity and phenolic contents of 'Monthong' durian aril at different ripening stages

Durian samples (100 g FW)	Mature	Ripe	Overripe
FRAP, reducing/antioxidant power (μMTE/100 g FW)	217	270	257
CUPRAC, cupric-reducing antioxidant capacity (μMTE/100 g FW)	1019	1112.7	1091
β-Carotene, % inhibition	64	76	70
Total polyphenols (mg GAE/100 g FW)	231	374	298
Quercetin (μg/100 g FW)	–	1200	–
Apigenin (μg/100 g FW)	–	620	4200
Campherol (μg/100 g FW)	1100	2200	8500

rapid growth phase until 56 DAA in 'Kradum' and 84 DAA in 'Monthong', when cell division ceases. During this rapid growth period the width and the length of 'Kradum' fruit grow at an equal rate, resulting in round-shaped fruit. However, the growth in the length of 'Monthong' fruit is faster than the width, resulting in oblong-shaped fruit (Koksungnoen and Siriphanich, 2008) (Fig. 5.1).

In details, the growth of the rind and fruit axis follows that of the whole fruit. However, the aril starts to develop at 35 DAA in both cultivars, but 'Kradum' ceases to grow after only three weeks while the aril of 'Monthong' continues to grow rapidly for up to 84 DAA before it levels off with a slower rate until a week before maturity (Fig. 5.1). At maturity the number of cell layers of the aril counting

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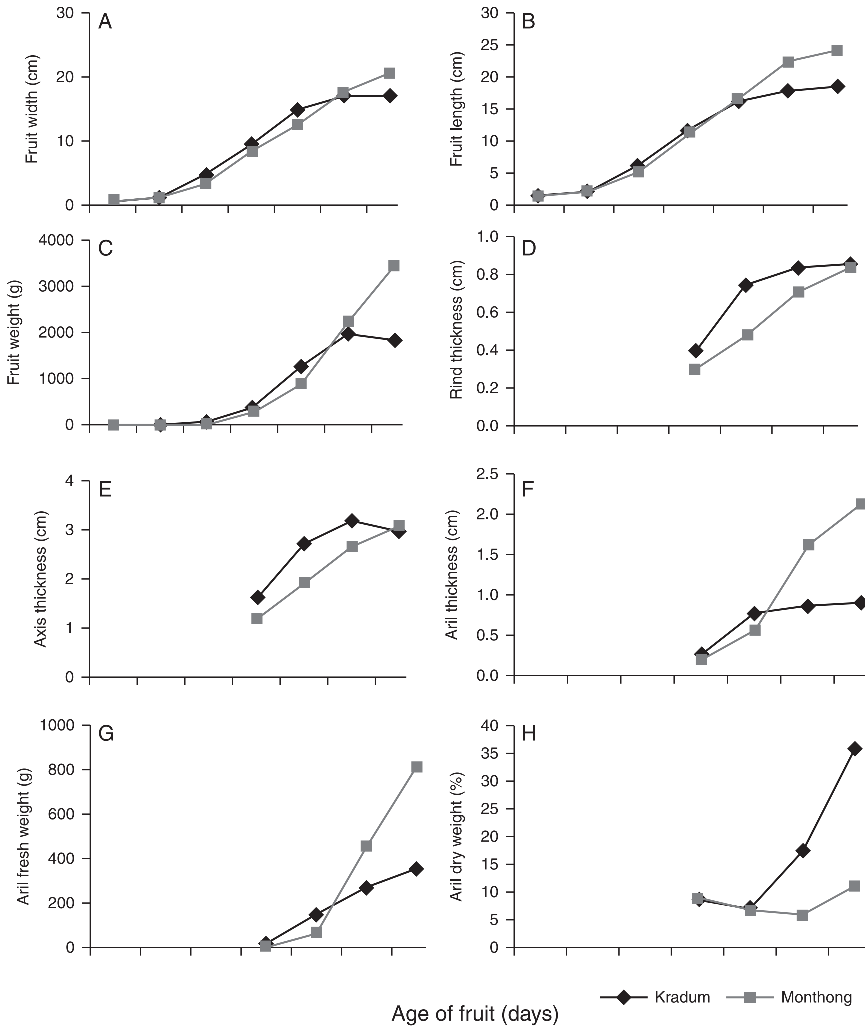

Fig. 5.1 Durian width (A), length (B), weight (C), rind thickness (D), axis thickness (E), aril thickness (F), aril fresh weight (G), aril dry weight (H) during growth and development of durians cv. 'Kradum' and 'Monthong'.

from the seed side to the rind side of 'Kradum' was one-third of that in Monthong. The cell size in both cultivars at their maturity is similar. Finally, the fresh weight of the aril of 'Monthong' is four times that of 'Kradum'.

Food accumulation in the aril, as determined in terms of sugar, starch, lipid and dry matter content, takes place only after the aril growth ceases or slows down. Starch grain is first observed at the end of the rapid fruit growth, and begins to disappear two weeks later. The accumulation of starch in the aril is not uniform, as indicated by the uneven iodine staining (Plate VIII E). The staining is brown

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instead of purple, indicating that starch in durian is amylopectin. This brown staining disappears after around 10–15 minutes. Carotenoid accumulation may commence earlier or later than starch and lipid, and continues to increase right up to the harvesting time. Sugar and lipid contents follow a similar pattern. The fatty acid composition of durian lipid is mostly unsaturated (Berry, 1981; Koksungnoen and Siriphanich, 2008; Sangwanangkul and Siriphanich, 2000).

5.2.2 Respiration and ethylene production

Durian has a climacteric respiration characteristic with a peak rate of around 200–250 mg CO_2 $kg^{-1}hr^{-1}$ at 25°C. Ethylene production ranges between 0.3 to 1.4 µl C_2H_4 kg^{-1} hr^{-1} during the pre-climacteric and 8 to 12 µl C_2H_4 $kg^{-1}hr^{-1}$ at its peak. Slow ripening cultivars have relatively lower ethylene production. Respiration and ethylene production peak at different temperatures in different cultivars (Siriphanich *et al.*, 1994). The peak of ethylene production occurs one day later than the respiration peak, particularly in those fruit harvested early (Booncherm, 1989).

Since the rind and the aril are easily separated, the respiration and ethylene production of both parts may be studied. Studying with dishes from both parts, Tongdee *et al.* (1992) reported that respiration and ethylene production was higher in the aril, probably because of wounding during the separation between the two parts. However, Booncherm and Siriphanich (1991) found that respiration rate and ethylene production of the rind was much higher than that of the aril. In addition, after the separation of the rind from the aril, the respiration and ethylene production in the rind continued to increase for a few days before declining. In the case of the aril, both rates declined soon after the separation. Later Chaprasart and Siriphanich (2000) reported that the ethylene production was detected in the aril before the rind. The higher ethylene production in the rind of durian was confirmed by the finding that 1-aminocyclopropane-1-carboxylic acid (ACC) synthase and ACC oxidase activities were higher and ACC content was lower in the rind than in the aril of both 'Chanee' and 'Monthong' durian.

Internal atmospheric composition changes with the ripening stage. CO_2 increases from 1–4% at harvest to 4–14% when ripened at 22°C, while ethylene increases from 0.5–1 $\mu l.L^{-1}$ to 3–7 $\mu l.L^{-1}$ (Tongdee *et al.*, 1990).

5.2.3 Ripening behavior

The first sign that durians are ripe is the odor of the fruit or the separation of the lower part of the fruit stem from the upper part. However, it has been observed that aril softening and the conversion of starch to sugar occur a week or two before fruit maturity. On the other hand, the color of the rind does not clearly change until the fruit is fully ripe and begins to dehisce.

As durian ripen, water content in the aril increases from about 40% to 70% when fully ripe. Starch content decreases from 9–11% to 1–3%. Total sugar increases from 5–10% to 20–30%, while reducing sugars increase from 1–3% to 2–6%. Lipid content increases from 2–3% to 3–5%. β-carotene, the main

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carotenoid, also increases during ripening from 220 IU to 660 IU in 'Chanee' and 25 to 180–230 IU in 'Monthong' (Sutthaphan, 1993). Softening of durian aril is caused by polgalacturonase (PG), pectin methylesterase and β-galactosidase, as all these enzymes increase during softening but the increase in PG is more pronounced, from a low level to a very high level (Ketsa and Daengkanit, 1999). It was also noticed that at 34°C PG activity was considerably lower than at 27°C but softening was about the same (Imsabai *et al.*, 2002). Later it was found that heating at 42°C inhibited PG activity by 50%, but deesterification and softening of the aril did not change much. Hence most probably other enzymes are also involved (Ketsa *et al.*, 2003).

Once fully ripe, durian fruit dehisce (Plate VIII F), starting at the stylar end upward to the fruit stem. The splitting also occurs first on the inner white tissue of the rind and progresses toward the green outer tissue. At this stage the aril is already very soft, starch has converted to sugar, the aril is very sweet and some time later becomes sour or bitter with a strong sulfurous odor, and is considered overripe. Sriyook *et al.* (1994) demonstrated that two factors are involved in the dehiscense process. The main factor is ethylene that induces the cell separation process, and the other is water loss from the rind, which results in the shrinking of the rind. The outer green part loses more water and shrinks more than the inner white part, causing a pulling force outward from the center of the fruit.

During storage of durian under low relative humidity conditions, durian may not dehisce, particularly among the early mature fruit, even though the aril inside turns ripe. This observation indicates that the dehiscence may not only require ethylene to induce the cell separation process along the dehiscence zone, but also require water for cell expansion near the separation site. However, a microscopic study did not observe any cell expansion along the dehiscence zone.

Khurnpoon and Siriphanich (2008) demonstrated that cyclohexanediamine tetraacetic acid (CDTA) soluble pectin in the abscission zone was higher than that in the rind region while the other wall compositions were similar. During the dehiscence period the enzymes β-D-glucanase and PG were induced in the dehiscence zone. They also observed that pectin, as well as hemicellulose, was degraded to smaller molecules and became more soluble, much in the same manner as observed during softening of many fruits.

5.3 Maturity and quality components and indices

5.3.1 Fruit size and shape

Normal size of durian fruit ranges from 1 to 5 kg, but the most preferred size is between 2–4 kg. The fruit shape is a very important quality parameter of durian, particularly in a cultivar such as 'Chanee' where pollination and fertilization is the limit. When fertilization is not complete and seeds are not all well developed, the locule becomes distorted reducing its quality. The fruit with distorted shape have more rind and less aril compared to the symmetrical ones. In 'Kradum', pollination and fertilization is almost always perfect and therefore the fruit

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develops into a symmetrical round shape. For the export market, durian should have at least three full locules, while the other two may have only a portion of the locule developed.

High aril to whole fruit ratio or thick aril and small or aborted seeds are important quality criteria for durians. The ratio depends on cultivars but a young tree may produce fruit with lower ratio due to the thick rind.

5.3.2 Fruit stem

The fruit stem is also an important parameter for durians in term of quality as well as its maturity index. During harvesting and handling of the fruit, the stem should not be broken or damaged by the spine of the other fruit, nor should it be shrivelled due to loss of water. Freedom from all these defects indicates freshness of the fruit. Durians on display in the supermarket often have their stems protected by wrapping with paper or banana leaves.

5.3.3 Lipid and fiber content of the pulp

A study on four Malaysian durian clones revealed that lipid content and fatty acid composition vary among these clones. D24 and D2, which received high organoleptic scores, contained a higher proportion of lipids but lower unsaturated fatty acid content compared to other clones. Durian cultivars containing lower palmitic to palmitoleic acid ratio had higher organoleptic quality (Berry, 1981). Fiber content also varies among cultivars. ‘Monthong’, the most popular cultivar at present, contains higher fiber content than the others.

5.3.4 Pigments

Young aril is white or cream in color. Later on β-carotene accumulates in the aril, turning its color to light or dark yellow depending on cultivars. Sutthaphan (1993) showed that the darker yellow color in ‘Chanee’ as compared to ‘Monthong’ was due to higher β-carotene content. If the trees are not healthy, the yellow color of the aril may be poorly developed, resulting in the appearance of yellow and white stripes along the cheek of the aril. During ripening, the accumulation of carotene continues, resulting in a more intense yellow color of the aril.

5.3.5 Antioxidant capacity

A study on antioxidant properties of ‘Monthong’ durian at different stages of ripening has shown that durian has a rather high antioxidant capacity (Table 5.3), higher than mangosteen, litchi, guava and mango. The antioxidant capacity is highly correlated with the polyphenols content. Caffeic acid and quercetin are the dominant antioxidant substances of ripe durian while apigenin and campherol are the dominant substances in overripe durian (Arancibia-Avila *et al.*, 2008; Haruenkit *et al.*, 2010; Toledo *et al.*, 2008).

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5.3.6 Volatiles

Durian aroma consists of two distinct components: one strong, pungent and onion-like, which is caused by sulfur-containing compounds, and the other fruit-like (fruity odor), also present in the pericarp, and caused by esters and alcohols (Baldry, 1972). At least 137 volatile constituents are reported from past studies. However, these studies have been done on different durian cultivars, from different origin and of different ripeness level. Hence, the compositions reported are different in both species and concentration. The sulfur-containing compounds included hydrogen sulfide, hydrodisulfides, dialkyl polysulfides, thilos and thioethers such as propanethiol, ethanethiol and methanethiol. The esters are ethylacetate, ethyl propanoate, ethyl 2-methylbutyrate, methyl propionate and 1,1-diethoxyethane. Ethanol and n-propanol were also found. Most ethyl esters decrease during storage while methyl, propyl and butyl ester increase. Table 5.4 shows the main volatiles found in three durian cultivars from Indonesia, Malaysia and Thailand (Chawengkijwanich, 2008a; Chin *et al.*, 2007; Weenen *et al.*, 1996).

5.3.7 Maturity and harvesting indices

Many indices are used to determine the maturity of durians, but no index can be used alone. A combination of maturity indices must be used in order to obtain accurate harvesting date. As durians develop close to maturity, many changes in chemical and physical characteristics occur inside the fruit but changes in

Table 5.4 Main volatiles in durians from three leading producing countries

Country	Clone	Sulfur compounds		Non-sulfur compounds	
		Name	Description	Name	Description
Indonesia	Koclak	*S*-ethyl thioacetate	Fruity, sulfury	3-hydroxy-2-butanone	Fruity
		Diethyl disulfide	Sulfury, cabbage, roasty	Ethyl 2-methylbutanoate	Fruity
		Ethyl 2-(methylthio) acetate	Sweet, sulfury, onion	2-hydroxy-3-pentanone	–
Malaysia	D24	Propanethiol	Cabbage, sweet, onion	Propyl propanoate	Apple, banana
		Diethyl disulfide	Sulfury, roasty, cabbage	Ethyl 2-methylbutanoate	Powerful green, apple
		Ethyl propyl disulfide	–	Propyl 2-methylbutanoate	–
Thailand	Monthong	Ethanethiol	Onion, rubber	Ethyl acetate	Fruity
		1-propanethiol	Cabbage	Ethyl propanoate	Rum and pineapple
		S-ethyl ethane thioate	Alliaceous, coffee	Ethyl 2-methy butanoate	Fruity

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appearance are rather subtle. Hence, harvesting durian with the right maturity is quite a difficult task. Only experienced farmers or workers can do the job correctly. The indices include:

Days from anthesis
The main index used to determine harvesting date of durian is the duration of fruit development from flowering to harvesting for each cultivar, ranging from 90 to 150 days after anthesis. However, all the fruit on the tree do not start to develop at the same time. In a good year when the weather during the dry season is quite dry and cool, the tree may bloom only once all over the canopy. If the weather is mild, flowering may occur sporadically in sets. The fruit settings may overlap, making it more difficult to distinguish between each successive set. During the fruit developmental period if the weather is rather warm, the fruit could be ready for early harvest. On the other hand, if it is cool the harvesting could be delayed. Furthermore, fruit in different positions on the tree or on the branch also develop at different rates. Farmers could also wait until the first fruit drop to start harvesting. A study on a Malaysian cultivar showed that during the first week 10% of the fruit dropped off followed by 25, 35, 15 and 15% in the following weeks (Nanthachai *et al.*, 1994).

Tapping sound
The second most used index is the tapping sound. Internally, as the fruit becomes mature, the aril starts to separate from the rind leaving space in between (Plate IX A). This space causes a hollow sound when the fruit is tapped. Farmers use the tapping sound to determine durian maturity. However, in dry weather and with a high rate of transpiration, the immature fruit may sound like a mature one when tapped.

It is not difficult to identify the fully mature fruit since the hollow sound is easy to note. However, these fruit cannot be shipped to distant markets. Other indices are also needed to correctly determine fruit that are mature but have not started the ripening process. These included the color of the rind, which changes slightly from fresh green to rusty green. At maturation, cork tissue develops at the base of durian spines and along the groove between the spines and in particular along the suture at the middle of each locule. The tips of the spine also turn brown or even black. These physical changes are responsible for the rusty green appearance. However, fruit on the outer canopy may look more mature than fruit on the inner canopy, even though they are at the same stage of maturity.

Dry matter content of aril
A study on the change in chemical composition during durian maturation revealed that all parameters varied considerably between seasons and orchards. Change in dry matter content of durian aril is the most consistent data obtained and can be used as a harvesting or maturity index (Plate IX B and Fig. 5.2) (Sangwanangkul and Siriphanich, 2000; Siriphanich and Khurnpoon, 2003; Kalayanamitra *et al.*, 2005).

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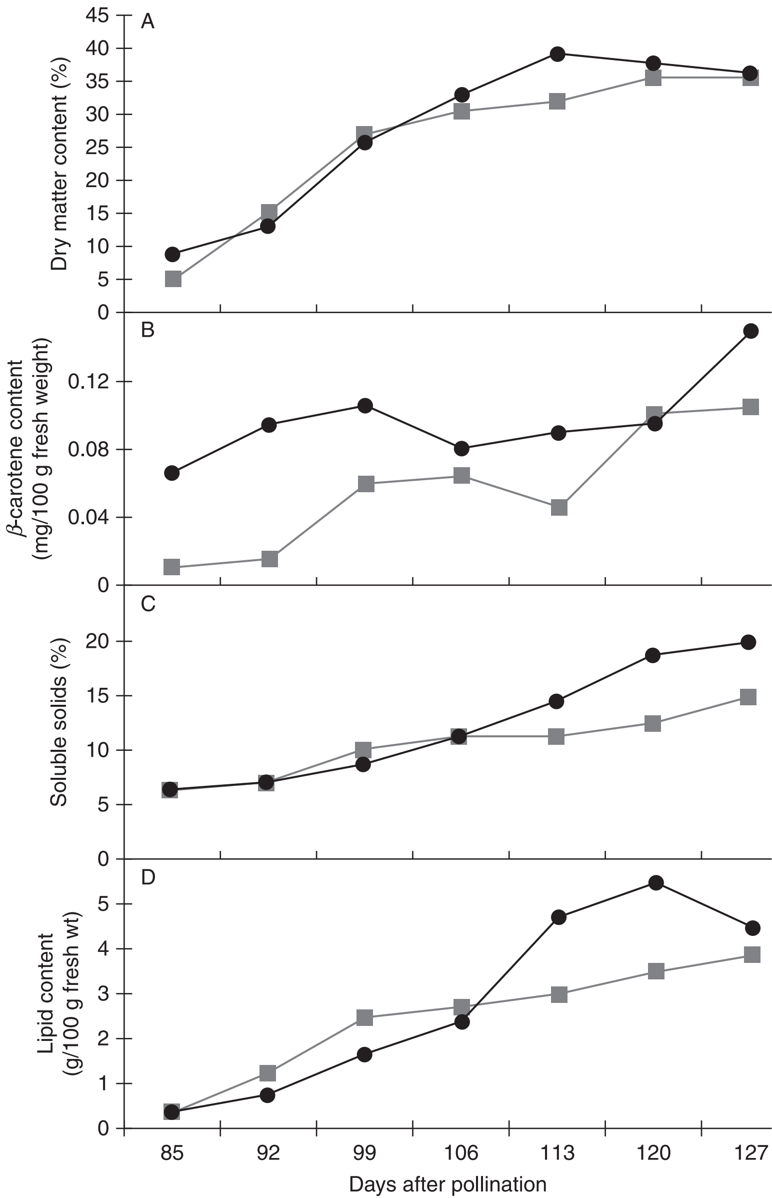

Fig. 5.2 Dry matter (A) β-carotene content (B), soluble solids content (C) and lipid content (D) of the aril of Monthong durians during fruit maturation grown at two locations, Chomphon (•) and Chanthaburi (■).

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It was shown that Kradum, Chanee and Monthong should be harvested when they have a minimum dry matter of 27, 30, and 32%. This information is adopted as a standard for exporting durian from Thailand. A study on shipment of Monthong durian of different dry matter content from Thailand to Taiwan showed that those that have less than 30% dry matter ripened poorly with no odor (Yiemchawe, 2003). Although dry matter of durian aril is accepted as a maturity standard in Thailand, it should be noted that the dry matter content is not a perfect index and does vary with locations and seasons. However, it is the most reliable method currently used and has highest coefficient correlation to sweetness, nuttiness, overall preference score and the number of days from anthesis to harvesting. In the study, some fruit with higher dry matter content than the standard was found to be inferior in eating quality. On the other hand, some may have lower dry matter content but appeared to be mature when tasted by the taste panelists (Siriphanich and Jerapat, 2005).

Strength of fruit stem

When the fruit is still young the stem is flexible and bends easily. As the fruit mature the phloem fiber in the fruit stem doubles during the last two weeks of fruit development making the stem resistant to a bending force. This change can be measured using a fruit firmness tester equipped with small multiple plunger-heads or by other sophisticated equipment that measures the elastic modulus of the fruit stem (Wattanavichean *et al.*, 2002). However, no equipment based on this parameter is applicable in the field at present, due to the variation of durians from different trees and orchards (Chattavongsin and Siriphanich, 1990).

Strength of spine

The spines appear more flexible when pressing two spines to each other with two fingers (Subhadrabandhu and Ketsa, 2001). This observation is due to the softening of the rind tissues, as shown in the fruit dehiscence study (Khurnpoon *et al.*, 2008).

Swelling around abscission zone

The area above and below the abscission zone of the fruit stem enlarges as the fruit becomes mature (Plate VIII B). It is more pronounced in ‘Monthong’ and ‘Kanyao’ cultivars (Nanthachai *et al.*, 1994; Thammabhutra, 2005).

Roughness of stem surface

The texture of the stem surface turns from smooth to rough (feeling like sand), except in ‘Kanyao’ cultivar (Vejchacheeva, 1986). This observation is due to the development of lenticels, which also occur on the base of spines upon fruit maturation.

Sweetness of sap from cut stem

Durian farmers notice that the sap oozing out from the fruit stem after cutting changes from viscous and tasteless in young durians to clear, less viscous and sweet in mature durians. A study by Chattavongsin and Siriphanich (1990) confirmed this

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observation in 'Chanee'. Total sugar increased significantly from 0.82% at 97 DAA to 1.84% at 111 DAA, but the increase was not significant in 'Monthong'.

Fruit specific gravity

The specific gravity of durian is always lower than 1.0 and decreases as the fruit matures. In 'Monthong', the fruit specific gravity decreases from about 0.95 when durians begin to mature to 0.9 when they are fully mature. However, for 'Kanyao' and 'Chanee' the change in specific gravity is minimal (Natvarathat, 1987). When durians are ripe the specific gravity also decreases to 0.8, due to water loss. Their volume also decreases by 1% per day (Jarimopas *et al.*, 1987).

The change in specific gravity of durian was used as a maturity index by weighing the fruit by hand; if it is relatively light in relation to its volume it is likely to be mature. On the other hand, if it is heavy it is likely to be immature (Vejchacheeva, 1986).

Based on this change, a group of engineers developed a tool to determine durian maturity systematically by measuring natural frequency (the frequency at the maximum power spectrum density) after tapping the fruit. It is claimed that the technique can be used at 85% accuracy to separate durians of one week's maturity difference and 100% of durians at two weeks' maturity difference. The size of the fruit has to be taken into account as well. The prototype built can sort durian at a rate of up to 4 tons per hour, using two operators (Terdwongworakul *et al.*, 1998; Sombatwong, 2003).

Another group developed a durian sorter using a floating technique, adjusting the specific gravity of water to 0.84 by pumping fine air bubbles into the water. The prototype can separate immature fruit from the mature ones at 76% accuracy (Yantarasri *et al.*, 2002).

A vibration method was studied by transferring a constant vibration directly through the fruit. The frequency responses from the vibration of durian are determined by using a light-intensity measurement set and transformed to power spectral density of frequency. The researcher correlated data obtained with a template power spectrum density of mature durians, based on dry matter of the aril, and revealed an accuracy of 76%.

In another development, an ultrasonic signal was transferred directly through durian in the middle of the fruit, the frequency response from durian was collected and transformed into a high frequency component to power spectrum density. The data were transformed into the absorption of ultrasonic signal. The decision was made by finding the correlation between the power spectrum density of the sample and that of the template from mature fruit, also on a dry matter basis. From 81 fruit studied, the accuracy was found to be 94% (Kongrattanaprasert *et al.*, 2001).

In addition, since moisture content decreases as durian fruit mature and ripen, engineers studied the way to detect durian moisture using neutron particle transmission or reflection (Chim-oye and Fuangfoong, 1999), microwave (Kittiamornkul *et al.*, 2007; Rutpralom and Kumhom, 2002), X-ray CT scan and nuclear magnetic resonance techniques (Yantarasri *et al.*, 1998). All studies reported good correlation between the parameters determined and the durian maturity.

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Most of these studies, however, only correlated the data to other maturity parameters such as number of DAA or dry matter of the aril, both of which had errors in relation to the physiological maturity of the fruit. The correlation with eating qualities or physiological maturity of durian was rarely made. Most studies also tried to measure only one parameter while the maturity of durian consists of many changes occurring in the aril as well as in the rind. In addition, the measurements were not aimed directly at the aril but at something, such as the stem or the air pocket between the aril and the rind, that changes in relation to the pulp. Last of all, the determinations were done when the fruit were unripe, not when they were ready to be consumed. Hence, application in commercial practice is not likely to be feasible in the near future.

5.4 Preharvest factors affecting fruit quality

Many consumers would not buy a whole durian fruit because they are not certain about the quality of the aril inside. Since maturity of durians is difficult to determine, poor-quality durians are often harvested. Preharvest factors affect the quality of the fruit directly. These factors include the internal and external factors listed below.

5.4.1 Internal factors

Fruit position: Fruit closer to the source or leaves are likely to mature earlier. Fruit from branches with many fruits mature later than those from single fruit branches (Kalayanamitra *et al.*, 2006). Determination of fruit maturity during harvesting should take this point into consideration. It was also found in 'Monthong' that about 330 healthy mature leaves are necessary to produce enough photosynthate for the development of a single fruit (Salakpetch, 2008). Hence, fruit from an unhealthy tree are likely to be of poor quality. The age of the tree also influences fruit quality. Young bearing trees produce fewer large fruit and many have thick rind and low aril to whole fruit ratio.

5.4.2 External factors

Light and temperature

Poor sunlight and low temperature during fruit growth result in a slow accumulation of the starch in the aril. Durians from trees that were shaded by 50% for one week before harvest ripened unevenly (Packcharoen, 2008). This study indicated that durian harvested during a prolonged period of cloudy skies may have less food accumulation in the aril and have poor ripening characteristics.

Rain and irrigation

A study on the level of water given to durian trees during fruit development indicated that heavy irrigation reduced the dry matter content of the aril, but heavy

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irrigation during the harvesting period only showed a trend of lower dry matter content (Jerapat and Siriphanich, 2008). These data combined with the shading study indicated that durian quality would be inferior if there is a period of heavy rain and cloudy skies during the harvesting period. In addition, heavy rain during fruit development could cause new leaf flushing. If flushing occurs early in the development of the fruit, young fruit are likely to drop off the tree. On the other hand, if flushing occurs when the fruit has already attained its full size and is accumulating food, the maturation process of the fruit will result in poor quality fruit (Mohpraman, 2009).

Heavy rain near the harvesting period causes durians to absorb a lot of water into the fruit. After the rain if it is still cloudy with high relative humidity, the fruit may develop water-soaked core disorder (see also section 5.6.2). It is recommended to irrigate durian trees at regular intervals and at an increasing rate during fruit development until the fruit begins to accumulate food. After that the amount of water applied to the tree should be reduced, and this will result in aril with less moisture and better color (Salakpetch, 2008).

Soil nutrients

It was believed that fertilizing durian trees with $K_2S_2O_4$, KCl and KNO_3 enhances the yellowish color of the aril, but most studies showed unclear results (Punnachit *et al.*, 1992; Poovarodom and Phanchindawan, 2006).

5.5 Postharvest handling factors affecting quality

5.5.1 Physical damage

Bruised durians are rarely found in the market. This is not because the fruit are strong, but because the bruising area is easily observed on the rind and becomes rotten quickly; hence bruised fruit are usually sorted out before entering the market. More commonly found are fruit with broken or damaged stems, occurring when the fruit are accidentally dropped during harvesting and handling. Wounding from the spine of the neighboring fruit is another common damage. It is the port of entry for postharvest pathogens.

5.5.2 Temperature

Durians are subject to chilling injury when exposed to low temperature. Mature and unripe fruit must be stored at 15°C or above. Ripe fruit may be held at 13°C for 7 days without any symptoms. A study of 'Chanee' cultivar showed that chilling symptoms could be observed within a week of storage at 5°C (Romphophak and Palakul, 1990). On the other hand, it was reported that durian could be stored as low as 4–5°C for five weeks, but chilling injury was not mentioned in this earlier report, so the fruit in this study was probably fully ripe. The rind might develop chilling symptoms but the aril was still in good edible condition. Studies on fresh cut durian (aril without rind) showed

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that the ripe aril can be stored for six weeks at 4°C (Praditduang, 1986; see section 5.10.1).

5.5.3 Humidity

Water loss from durians can be very high. In normal tropical conditions (25–30°C, 65–85% relative humidity) the rate of water loss can reach up to 4% per day. This high rate of water loss is due to its high spine surface area and high rate of respiration. The volume of the fruit can also be reduced by up to 1% per day (Jarimopas, 1987).

This high rate of transpiration is not enough to release heat from durian respiration. The temperature inside the fruit, when fully ripe, was recorded at 5°C higher compared to the temperature at harvest and about 3°C higher than the atmospheric temperature. The accumulation of heat causes durians to ripen very fast once the process starts.

It was shown that ripening of durian was best at relatively high temperatures (33°C) (Pangkool, 1993). It is possible that ripening for good eating quality durian could be achieved at lower temperatures, if they are allowed to proceed to their prime ripening stage.

Although Ketsa and Pangkool (1994) reported similar durian aril quality after ripening at 75 and 93% relative humidity, it is commonly observed that ripening at lower humidity will yield better eating quality of the aril having dry and not watery texture. However, durians ripened at low relative humidity should be quite mature if not fully mature. Otherwise ripening will take longer and too much water loss will occur during the ripening period which may limit the dehiscence process, and the fruit may turn out to be very difficult to split open. In this case ethylene is needed to enhance the ripening process. Water loss from durian is one of the two factors causing fruit dehiscence. A high rate of water loss induces a higher rate of durian dehiscence. However, too much water loss will limit the dehiscence process and cause cracking of the rind outside the suture at the middle of the fruit.

5.5.4 Atmosphere

Proper atmospheric composition is required for durian to ripen normally. In an incident when the fruit were transported in a truck well covered with canvas for one day from the east to the south of Thailand, the fruit could not ripen at the destination. It was thought that the temperature inside the truck increased to a very high level. The respiration rate of durian went up, reducing oxygen and raising the carbon dioxide level to a point that prevented ripening. Tongdee *et al.* (1990) reported that durian were highly sensitive to low oxygen. At an oxygen level lower than 7% at 22°C durians' ripening processes could be blocked (see also section 5.9.5). Hence during storage and transportation, adequate ventilation must be achieved (see also section 5.9.4).

Ethylene gas induces durian ripening including the dehiscence. A study using different types and concentrations of coatings to reduce water loss revealed that

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those having a higher concentration of ethylene inside the fruit dehisce more than the others (Sriyook *et al.*, 1994).

5.5.5 Others

A study conducted (Siriphanich and Jarimopas, 1993) by interviewing domestic collectors, wholesalers and retailers, revealed that overall postharvest losses in durian were between 6.5 and 13.5% in 'Chanee' and only 5.5 to 8.5% in 'Monthong', probably due to 'Monthong' having a slower ripening rate. There were variations in the loss at different trader levels and seasons. Lower losses were found at the wholesale level while loss at the retail level was highest. Most of the losses were due to the harvesting of durian while they are still immature, followed by disease incidence. Hence, early in the season there was more than 5% loss of durian compared to only 1% late in the season. In mid season there was a higher percentage of damaged fruit due to broken stems. This is probably because there were a lot of durians ready for harvest; the workers must work fast. Late in the season losses are commonly three times higher from disease incidence, up to 3%, probably because of higher rainfall and humidity at this time.

At present it is thought that the domestic loss level remains the same as that reported in 1993, since handling procedures for the domestic market rarely change and only transportation has slightly improved. For exportation, the technology has improved significantly. There are quality standards for durians, more cold rooms and refrigerated containers available for exporters to pre-cool durians. Experienced exporters reported less than 1% loss each year. However, new exporters can face total loss mostly due to inexperience in collecting good quality fruit from reliable suppliers and farmers.

5.6 Physiological disorders

5.6.1 Chilling injury

Chilling injury (CI) symptoms begin with black color development along the groove between spines, and later the whole rind turns black (Plate IX C). The aril may ripen abnormally or remain hard. In severe cases the entire ripening process is inhibited (see also section 5.5.2).

5.6.2 Water-soaked core

Water-soaked core, also known as wet core, appears first as a mushy and watery area at the axis of the fruit followed by the white funiculus tissue and then the aril tissue nearby. At this stage the aril has a dull taste. In a severe case, the aril of the whole fruit can be watery and very soft in texture, and fermented. This disorder usually occurs in fruit harvested after heavy rain, and is found more prominently in 'Kanyao' and 'Chanee' cultivars and much less in 'Monthong'. It is also found more in young bearing trees than in older ones. A study comparing the watering rate of 'Chanee' and

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'Kanyao' trees at a rate of 400–1600 liters per week (Leeangkulsatein and Hiranpradit, 1987) showed that with a higher level of watering, a slightly but significantly higher water-soaked core was observed in 'Chanee'. In 'Kanyao', there was no difference in the development of water soaked core between different watering levels. If the experiment was conducted in such a way that relative humidity was also controlled, simulating rainfall level, the result should be clearer in both cultivars. Potassium deficiency is thought to be one of the factors causing this disorder; however, there was no strong evidence to support this claim. Fertilizing with potassium one month before harvest, draining the soil immediately after heavy rain and delaying harvesting by two days are recommended (Ahmad Tarmizi and Nanthachai, 1994).

5.6.3 Aril tip browning

Aril tip browning or aril necrosis is a disorder where the edges of the aril die off and turn brown or black, particularly on the dorsal side of the pulp unit (Ahmad Tarmizi and Nanthachai, 1994). It is the aril tissue that did not develop to its full extent early in the fruit development. This disorder is similar to the disorder found in lychee and longan of which the pulp is also the aril tissue. It is often found in fruit from young or unhealthy trees. It is believed that during the early development of the aril if there is a disruption of water or photosynthate supply from the tree the aril will stop growing and die off to allow the earlier part to develop further. No scientific evidence was found to support this explanation. However, farmers who take good care of the tree, by supplying it with enough fertilizer and water, do not face this problem.

5.6.4 Uneven fruit ripening

Uneven ripening in durian is a common disorder observed in all durian growing areas (Ahmad Tarmizi and Nanthachai, 1994). It is mostly observed in larger fruit of 'D24' and 'Monthong' or in fruit of the late cultivars that are usually larger than the early cultivars. In mild cases the aril around some seeds of a durian or some parts of the aril around the same seed remains firm in texture while other parts are already soft. In severe cases, the aril remains hard, dry, white and tasteless. It has been suggested that the cause may be multifactor (George, 1996) including nutrition, environment and water availability. It was later shown that this disorder is actually the problem of fruit maturity. Investigating harvesting period, shading and leaf flushing experiments (Table 5.5), the results indicated that any factor that disrupts the fruit growth and development could cause this disorder. In addition, if the growth inhibiting factor is removed and the fruit are allowed to develop for a little longer, uneven ripening is minimized or eliminated. It is suggested that in natural conditions when there is a cloudy and rainy period during the durian harvesting season, harvesting should be delayed in order to obtain fruit with less uneven ripening disorder. Treating durians with high concentrations of ethephon could not alleviate this disorder. Hence, uneven fruit ripening in durians was not simply the lack of their ability to produce ethylene. One possible explanation is that the affected durian might have an inadequate amount

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Table 5.5 Firmness and uneven ripening score of Monthong durians harvested from non-flushing and leaf flushing trees (A), from unshaded and shaded trees (B) and from fruit treated or not treated with ethephon (C)

A. Leaf flushing experiment	Means		*P*-value[1]	Total variance		*P*-value[1]
	Non-flushing	Leaf flushing		Non-flushing	Leaf flushing	
Firmness (N)	8.5	9.2	0.58	30.82	71.82	<0.001
Uneven ripening score	2.54	3.09	<0.001			
B. Shading experiment	**Means**		***P*-value[1]**	**Total variance**		***P*-value[1]**
	Control	Shade 1 wk.		Control	Shade 1 wk.	
Firmness (N)	8.7	10.3	0.096	7.42	17.65	<0.0001
Uneven ripening score	2.53	2.67	0.031			
C. Ethephon experiment	**Means**		***P*-value[1]**	**Total variance**		***P*-value[1]**
	Control	Ethephon		Control	Ethephon	
Firmness (N)	9.6	7.4	0.0003	11.57	10.09	0.413
Uneven ripening score	2.53	2.51	0.38			

[1] *P*-value >0.05 = non-significant

of ethylene receptor to bind with ethylene and consequently induce ripening (Pakcharoen, 2008; Mohpraman, 2006; Tisarum, 2006).

5.7 Pathological disorders

Fruit rot is not a serious problem in local markets because the fruit tend to be ripe and are ready to be consumed before disease development. However, under humid and poor ventilation storage conditions, particularly for an extended period, fruit rot could be a serious problem.

5.7.1 *Phytopthora*

Pathologists had identified numerous fungi on rotten durians. However, the most serious cause of durian fruit rot is *Phytopthora palmivora* Butler which also causes the root and trunk rot, known also as patch canker. The fungus may attack durian at any stage but a suitable environment for the infection is during the rainy season, at the time the fruit are mature or nearly so. The rain and wind carry spores or mycelia on to the fruit, particularly those on the lower part of the tree. The main infected portion of the fruit is at the stylar end where rainwater dries out at the slowest rate and concentrates the fungal spore. It has been found that once the spores land on the fruit surface, with suitable conditions, 50% of the fruit can be infected in seven hours and 100% in 17 hours. The symptom is water-soaked spots on the fruit surface which become greyish brown and expand in a circle or oval shape (Plate IX D) as well as deeper into the aril. When the fruit matures, it

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easily splits open. 'Kradum' and 'Chanee' fruit are more susceptible to this fungus than 'Monthong'. However, more problems were found on 'Monthong' during postharvest handling because 'Monthong' ripens more slowly than the others. The others may ripen before the fungal development occurs (Kobayashi, 1978; O'Gara *et al.*, 2004; Sangchote, 2000; Vichitrananda, 1988).

This fungus can be effectively controlled by spraying in the orchard regularly. Postharvest dipping with Fosetyl aluminum [aluminium tris(ethyl phosphonate)] at 2000–4000 μgL^{-1} is recommended (Siew *et al.*, 1994). The fungicide application should be done within 24 hours after harvest, although a study showed that delay in treating with the fungicide for up to 36 hours did not affect its effectiveness (Romphophak *et al.*, 1997).

5.7.2 *Lasiodiplodia* and others

The other fruit rot is shown to be caused by *Lasiodiplodia theobromae*. This fungus can only get into the fruit via a wound, and it cannot make a direct infection. After inoculation through a wound it takes more than six hours for fruit to develop the disease. The early symptom of this disease is quite similar to that caused by *Phytopthora palmivora*, appearing as brown circles on the rind particularly at the stylar end. The circle expands outward on the surface and inward into the aril. The difference between the two fungi is that the tissue infected with *Phytopthora* is moist as compared to that infected with *Lasiodiplodia*, which appears rather dry. Later in the development of the two fungi the symptoms become much easier to identify, appearing as white to grey powdery masses of sporangia for *Phythopthora* and black mycelium in the case of *Lasiodiplodia* (Lim, 1993; Sangchote, 2000). *Phomopsis* sp and *Colletotrichum gloeosporioides* may also infect durians but not virulently, even when inoculated through a wound. Dipping for five minutes in Thiabendazole at 1000 μgL^{-1} or Carbendazim at 500 μgL^{-1} is effective in controlling these fungi. Dipping in 500 μgL^{-1} Imazalil no later than six hours after harvest is very effective in controlling the mycelium growth of *L. theobromae* as well as its spore germination (Sangchote, 2000).

Postharvest disease on durian is the main limiting factor for extending its storage life and expanding its export to overseas markets. This is probably not only because of the wound caused by the spines of the other durians, but also the existence of the trichome on the durian surface. During postharvest cleaning, a high pressure air jet is usually used to remove dirt, insects and mold from the surface of the fruit. The process also removes the surface trichome leaving wounds on the fruit surface and enabling various fungi to enter it easily.

5.8 Insect pests and their control

Despite having thick and relatively tough skin, durians still have a number of insect pests. Those of postharvest concern are mealy bugs and scale insects on the fruit surface, and fruit borers.

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5.8.1 Surface insects

Mealy bug is of the *Pseudococcus* species. Their appearances always occur together with black sooty mold that thrives on the honeydew excreted from the mealy bug (Sirisingh *et al.*, 1994). Scale insects are of the *Coccus* species. Both insects are usually carried on to the fruit by ants. Hence controlling the ant population in the orchard by banding durian branches with pesticide or petroleum oil is an important cultivation practice. Spraying the fruit directly with water is also effective in removing the insect.

After harvest, the two species are easily removed by high pressure air or water jet. In the case of black mold, brushing may be needed. When the insects are removed, they often leave a patch of light green on the surface of the fruit. Hence heavily infected fruit are not suitable for export even after the insects are removed. The high pressure air or water jet not only removes insects but also removes the peltate trichome on the fruit surface, leaving durians with tiny wounds and lighter rind color after the cleaning process. Consequently fruit are susceptible to fungal infection.

5.8.2 Internal insects

Another group of insects infest the interior of the fruit. Seed borer *Mudaria magniplaga* Walker was first reported in 1980 in Malaysia (Sirisingh *et al.*, 1994). In Thailand it was reported as *M. luteileprosa* Holloway (Buara, 1996). This insect is a serious pest for durian, attacking the fruit at any stage but mostly young fruit at 4–7 weeks after anthesis. The adults lay eggs on the fruit surface, usually on the top part of the fruit. The larvae feed on the surface and penetrate through the rind at the base of the spine through the aril to feed in the seed for about a month. The larvae are purplish red when mature and bore out of the fruit to pupate in the soil, leaving a round hole, 5–8 mm in diameter. If the infection occurs early in fruit development, the damaged fruit drops to the ground. If infection occurs later, the larvae may be found inside the harvested fruit. Preharvest spray to control the insect is very important. Inspection for the insect after harvest is possible but they may easily be missed.

Other borers include *Monogatus puntiferalis* Guene, reported in Malaysia and *Conogethes punctiferalis* Guene reported in Thailand, which is a rind borer (Disthaporn *et al.*, 1996). It first feeds on the surface, then penetrates into the fruit, sometimes feeding on the aril. The full grown lavae have black spots scattered along the body. They pupate in between spines covered with leaf and their own faecae. However, detection of this insect is quite easy, hence it is not a serious postharvest problem.

5.9 Postharvest handling practices

Postharvest operations on durian are rather cumbersome, involving as many as 15 steps as shown in Fig. 5.3.

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Fig. 5.3 Handling steps for durian exported from Thailand: (a) Cutting and tossing; (b) Catching; (c) Collecting into basket; (d) Sorting and loading; (e) Unloading at packinghouse; (f) Sorting; (g) Applying ethephon; (h) Weighing; (i) Blowing with air jet; (j) Dipping in fungicide; (k) Drying; (l) Adding sticker; (m) Packaging in carton; (n) Weighing; (o) Palleting; (p) Loading and cooling in container. Drawing by Kavin Siriariyaporn.

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5.9.1 Harvest operations

For local consumption where consumers prefer fully mature and fully ripe durian the fruit can be allowed to drop to the ground. However, this is only for consumption around the planting area. Fruit for other areas or markets need to be harvested directly from the tree. In the past, harvesting durian was done by one worker climbing up the tree, reaching the fruit, checking its maturity and cutting the fruit and hoisting it down to the ground with a rope or placing it in a basket before hoisting it to the ground. This process is rather slow. In commercial orchards in Thailand, workers work in pairs, one climbs up the tree, harvests the fruit and tosses it to the other worker waiting on the ground. The second worker catches the falling fruit with a jute sack in his hands. The tossing of the fruit must be aimed to let the fruit fall into the jute sack on its sides or its base, not on its stem. If the fruit lands on its stem, the stem will break and lower the fruit value. A pair of workers can harvest up to 2500 fruit or 5–8 tons per day.

While farmers use 'number of days from flowering to harvest' as the key index for harvesting (see other indices in sections 5.3.7 and 5.3.8), they use the term 'maturity percentage' from 70 to 100% for their communication with the buyers. One hundred percent maturity refers to the stage when the fruit are already ripe (130 DAA in 'Monthong') and ready to drop off the tree and have no storage life. Ninety percent maturity refers to the stage of fully mature fruit (120–125 DAA for 'Monthong'), where climacteric respiration is already initiated and storage life is less than 3–4 days. This fruit is only suitable for the domestic market, or for export by air. The quality is excellent and no ethylene is needed for its ripening. Eighty percent maturity refers to the mature green stage durian (110–115 DAA for 'Monthong'). It can be advanced mature green (+5 days) or less mature green (−5 days) for sea shipment duration of 7–10 days and 10–14 days, respectively. Seventy percent maturity is the minimum maturity at which durian can be harvested with acceptable eating quality. The fruit must be treated with ethylene or ethephon. This maturity stage is equivalent to 95–105 DAA in 'Monthong'. However, harvesting at this maturity stage is rather risky. There is a high chance of harvesting immature fruit so that when treated with ethylene the flesh will become soft but remain white or creamy in color without aroma or sweet taste.

Once the fruit has been caught in the jute sack, it must be taken out and into a basket or a lorry or other vehicle in the orchard, avoiding contact with the ground or dirty surface to prevent fungal contamination. Harvested durians are then taken to the farmers' packing shed for preliminary sorting. Undersized and oversized, immature or over mature, damaged or infected fruit are removed. The sorted fruit are then loaded into a pick-up truck to be taken to the collector or exporter.

Durian for export must be obtained only from a relatively well kept and clean orchard, having no rotten fruit or broken branches left on the orchard floor. The orchard should also have good drainage. The exporter must visit the orchard in advance and make sure that the orchard is relatively free of *Phytopthora*. Infected trees must be treated. The infected bark must be removed and the wound treated with fungicide. The tree should be healthy. The branches should be full of dark green leaves. The amount of fruit on the tree must be in a good proportion to the

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tree's condition. This is an important criterion since unhealthy trees can produce poor quality fruit including those having uneven fruit ripening characteristics.

5.9.2 Packinghouse practices

At the packinghouse, durian should be sorted one by one by an expert to determine their maturity and other minimum requirements. Undersized, oversized and misshapen fruits and those with other defects should be rejected and returned to the farmer. The stems of selected fruits are cut off to about 1 cm in length. The newly cut surface is treated with a 1 to 48% active ingredient of ethephon, depending on the fruit maturity. The fruit are then weighed in bulk and moved to the next stage of the operation.

Cleaning of durians is usually done by using a high pressure air gun to remove dirt, insects and mold from the surface of the fruit. Sizing at this stage is usually minimized since the collectors or exporters inform farmers of the range of durian size that they will accept. Slightly different fruit size is needed in order to fit a certain number of fruit into one box of a certain weight.

Fungicide dipping is needed for durian (see section 5.6). Some exporters add 1000 to 3000 μgL^{-1} of ethephon, if they were not treated during the sorting, with the fungicide solution to ripen the fruit in transit. By the time durians arrive at their destination the fruit are ready to be consumed.

After dipping, durians are allowed to dry in piles of three to four layers on pallets. After drying, they are then packed in corrugated boxes. Generally two box sizes are in use: the 10 kg box of 2–4 fruit, and a 20 kg box of 6–8 fruit. In the box, each durian is protected from the spines of the others with cardboard partitioning. However, for domestic markets boxes are not used. Fruit are loaded directly onto pickup or six wheel trucks.

Variations in packinghouse operation do exist. Some exporters do not apply ethephon to durians, rather they allow durians to ripen naturally to some degree in the packinghouse. Once durians start to ripen, which can be checked by tapping the fruit with a rattan stick, they will be packed and shipped. This practice ensures that immature or less mature fruit will not be shipped out.

5.9.3 Control of ripening and senescence

To delay ripening, the use of coating materials is possible. In ambient tropical conditions coating can reduce weight loss by 25–35%, delay the dehiscence and double the shelf life. Coating with materials containing a high concentration of shellac is not recommended since it gives an unnatural shiny appearance. For domestic markets the coating may be delayed for up to 3 days, and its effect on extending shelf life remains positive (Chaiprasart, 1992). For export in the current shipping period of 1–2 weeks to China, the benefit of coating is rather limited and may be of no benefit at all. In commercial practice, waxing is not recommended since most export markets have no facility to store or to ripen the fruit. Importers prefer to receive durians that are ready to be sold and consumed. However, this

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recommendation is for shipment of 7–14 days. For longer distances coating may be a good choice but good fungal control is essential.

1-MCP application was also studied, where ripening is delayed and durian can be stored for up to 30 days at 15°C. However, the use of 1-MCP is not recommended, since treated fruit become very difficult to split open (Suwanakul *et al.*, 2002). It is believed that the amount of 1-MCP bound to the receptor in the dehiscence zone may be much greater than that bound in the aril inside, since 1-MCP must penetrate from the outside through the rind to the aril tissues.

Other plant growth regulators including auxin, gibberellin, cytokinin, daminozide and mepiquat chloride were tested on durians to delay ripening. Only gibberellic acid (GA) at 50 μgL^{-1} delays the degreening process of the rind and its dehiscence process by 2 days at room temperature. No clear effect of GA on the ripening of the aril was found (Sriyook *et al.*, 1994). The combination of GA and coating materials did not give additional effects. Commercial application of GA is also not recommended at present, since the green appearance of durian indicates that the fruit are immature.

5.9.4 Recommended storage and shipping conditions

Recommended storage or shipping temperature of durian is between 14–16°C (Anon., 1977). Fruit that have already begun the ripening process can be stored at 13°C. For marine shipment temperature is usually set at 14°C. This is because in most cases durian are not precooled before loading into the container.

Precooling before loading into shipping containers is needed when durian is quite mature and begins to ripen. If the fruit have not been precooled the heat of respiration may be too great for the refrigeration unit to bring down the temperature. Durian temperature, measured at the center of the fruit, is a good indicator of whether durians should be precooled or not. At harvest the temperature of unripe mature durian is about 26–27°C when the average air temperature is about 29°C. If the fruit's temperature is over 28°C, the fruit should be precooled. However, if the temperature is 30°C or over it should not be shipped overseas.

Sorting is the key operation to successfully exporting durian. Not only it is important to sort for mature durian, but also important to sort durians into different maturities, in order to handle them correctly. For example, in the middle of the durian season, when sale at the destination may not be brisk, less mature durian should be loaded first and more mature durian should be loaded later in order to sell the more mature fruit first. For a shipment time of 7 days, advance mature green is the optimum stage and the less mature green fruit should make up no more than 25% of the total shipment. For 10–14 days shipment, the less mature green is the optimum stage and the mature green fruit should make up no more than 15% of the total (Anon., 1997).

Storage studies usually record storage life of durian as being up to 3 weeks but in commercial practice 2 weeks is the maximum, since conditions during the laboratory experiment and commercial conditions are quite different. Under commercial conditions it takes 1–3 days before durian are ready to be loaded into the container. Once in the container, durian temperature is usually reduced slowly.

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Normally it takes about 24 hours or longer to bring the fruit temperature to the set temperature. In addition, ethylene concentration in the container is usually quite high, ranging between 1–8 ppm, due to the higher ratio between the volume of the fruit and the container as compared to that in the laboratory.

There are no studies on the optimum storage humidity for durian, but it is recommended to be stored at 85–90% (Anon., 1977). The relative humidity during storage of durian should not be near saturation point. This is because the contamination of fungal spores on the surface of the fruit may lead to disease development. In a sea container, it is recommended to set the ventilation rate at 40% to maintain proper humidity inside the container. Less than 40% ventilation results in condensation inside the container and high disease incidence. Under ambient conditions it is recommended to leave the fruit in a pile of 4–5 layers on pallets to allow good air ventilation for the fruit to release its heat of respiration and slow down its ripening process.

Shipment by air is not uncommon, but the packaging must be carefully done to prevent durian odor getting into the passenger cabin. An old method to prevent durian odor is to place basil leaves inside durian boxes. It is believed that volatiles released from basil leaves react with durian volatiles and neutralize the odor. Activated charcoal of 50 g can be used to absorb odor of 2 kg durian in a polypropylene bag for 24 hours. On the other hand the durian box may be wrapped with plastic, but it must be removed on arrival at the destination. Shrink packaging of ripe durian with PVC film of 40 μm thickness can prevent the leakage of durian odor for at least 48 hours provided that the seal is perfect. The technique cannot be used with unripe durian since the airtight condition limits respiration and normal ripening process (Anon., 1987).

Morris and Jobling (2002) reported the use of an impermeable package with a hole, covered with a permeable sachet containing an odor-absorbing powder. This packaging allows enough gas exchange for normal ripening processes to occur, while preventing the release of durian volatiles outside the package. Chawengkijwanich *et al.* (2008b) developed a TiO_2 coated film that can decompose durian volatiles in the packages after ultraviolet A illumination for 1 hour.

5.9.5 Controlled and modified atmosphere

A study by Tongdee *et al.* (1990) showed that low oxygen atmosphere between 5–7.5% at 22°C could extend storage life of 85% maturity durian to about 7 days with 4 days of shelf life, compared to only 5 days under normal atmospheric conditions. High CO_2 atmosphere of 5% slowed down the ripening process. At higher concentrations conflicting data were reported. In one report at 10% CO_2 uneven ripening was observed. However, in another report, the combination of 10% oxygen and 10% CO_2 kept durian in good condittion but did not give extra benefit. At 15% CO_2 and higher, ripening was permanently blocked.

In 2000 a study on controlled atmosphere storage of durian at 15°C was conducted. Rattanachinakorn *et al.* (2000) showed that with oxygen at or below 7% the firmness of the aril was maintained but the yellow color development of the aril

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was poor and the fruit ripened unevenly. At 10% oxygen, durians can be stored for up to 4 weeks but the color development of the aril is still poor. Ripening these fruit with ethylene has been recommended. Currently controlled atmosphere (CA) on durian is not used commercially. This is because the very high humidity under the airtight conditions of the CA storage, together with the relatively high temperature (14–16°C), results in high mold even when treated with fungicides. The use of shrink wrap was also reported to extend storage life of 'D24' durian at 8°C for 8 weeks, by preventing splitting of the fruit by as much as 75% (Mohamed, 1990).

5.10 Processing

Before being processed, durians must be split or cut open in such a way as to minimize damage done to the aril and the production cost. For fully ripe fruit, splitting the fruit and removing durian aril from the fruit for processing is easy. The aril of this ripeness is suitable for making durian paste. For those that are half ripe or just ripe, it is rather difficult and requires special techniques and equipment. There are two ways to split open the fruit. One is by using a knife to cut along the suture on the rind of two opposite locules, from the stylar end to the stem end and also along the fruit axis between the two locules, then pulling the two portions apart. This method can be used on fruit that has ripened to some extent and the dehiscence process proceeded to some degree. The aril at this ripeness is suitable for fresh cut. However, if the fruit are quite ripe and the aril is already soft, removing the aril from them may cause unattractive bruises on the arils. Ethylene or ethephon application can facilitate the removal of the aril from the fruit by enhancing the dehiscence process more than the softening of the aril. This is because the rind receives a higher concentration of ethylene than the aril inside.

On the other hand, if the fruit are unripe or just ripe and the aril is quite firm, the fruit may be cut on each side of an individual locule from the stem end to the stylar end (in a rugby football shape) to remove the rind that covers the aril first. The pulp unit is still strongly attached to the fruit axis and must be cut at the base to allow its removal. The pulp unit obtained in this way is usually hard and suitable for processing into durian chip, flour or powder.

A number of tools have been invented to facilitate the opening of durians. Many of them are quite efficient, but all are also large. Plate IX E shows an example (Sihawong and Phoniyom, 1999). One operator can open 400 kg of durian per day. These tools are usually used only in processing plants. Most retailers still prefer to use a knife and the hands.

5.10.1 Fresh-cut durian

Durian at the half-ripe stage when the aril is still relatively firm is suitable for fresh-cut preparation. The pulp units (aril and seed) from a fully ripe durian having soft aril are often bruised during the preparation and are unattractive. The pulp unit of 'Chanee' durian packed on a foam tray and wrapped with PVC film may be kept

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for 30 days at 4°C (Booncherm and Siriphanich, 1991; Praditduang, 1986; Voon, 2006). At 8 and 12°C the shelf life was 16 and 12 days, respectively. Using low density polyethylene (LDPE) film wrapping, 36 and 28 days of storage life at 4 and 8 °C was also reported (Sudto *et al.*, 2006). The difference in storage duration may also depend on the durian cultivar and their ripening stages. For longer storage duration, fresh-cut durian should be packed in plastic containers sealed with LDPE film and stored at 4°C. In this case it can be stored for up to 45 days. Deseeded durian aril did not store well, due to greater physical damage on the aril in addition to the damage on the white funiculus during the removal of the pulp unit from the fruit axis. It should be noted that the surface of the aril is covered with a thick cuticle of the epidermal tissue providing relatively good protection from microbial infection. Deterioration of fresh cut durian starts at the white funiculus tissue by bacterial yeast or mold growth. Hence preparation of fresh cut durian must be done in a clean atmosphere free of bacteria or fungal spores or mycelium.

Durian pulp unit removed from the fruit and stored in ambient conditions continue the ripening process at a slightly slower rate than that in intact fruit. Packing in trays wrapped with PVC film delayed the process slightly (Sudto *et al.*, 2006). Adding ethylene absorbance in the package delayed the ripening slightly further, but adding ethylene to the pulp unit did not enhance the ripening rate. Storage at 4–5°C dramatically reduces the ripening rate. 1-MCP fumigation at 50 nlL^{-1} for 12 hours slightly delayed softening and the conversion of starch to sugar of fresh-cut durian (Sudto and Uthairatanakij, 2007).

Firmness of the aril during storage may increase, but this is because of the toughening of the epidermal tissue covering the surface. Storage at ambient temperature may result in acidification, probably because of over-ripeness (Voon, 2006).

5.10.2 Frozen durian (pulp unit or whole fruit)

Half ripe or fully ripe durian can be frozen and stored for 6–12 months at −25°C (Paweenakarn, 1987). Whole frozen durian is preferred by the consumer over frozen pulp unit, since the pulp unit in the intact fruit retained its original shape as well as its taste. Frozen pulp unit loses its shape and may appear bruised during thawing. The main problem in preparing whole frozen durian is the cracking of the fruit during the freezing process. This problem can be overcome by holding the fruit at 8–10°C for a few days before freezing. Fully ripe or overripe durian aril may also be frozen for later use as raw material in making other durian products, particularly durian paste.

5.10.3 Durian chip

Mature but unripe durian aril can be sliced and fried to make durian chips that are light yellow in color. ‘Monthong’ durian is the most suitable cultivar to make this product due to its thick aril that can be sliced into larger chips. The fruit should be unripe with a low sugar level. The arils from fruit that have already begun their ripening process, containing a substantial level of sugar, produce brown-colored

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chips. These brown chips are better in taste, having a sweeter taste together with a slight durian flavor, but obtain lower prices compared to the yellow chips. The chips can be stored in sealed metal containers for several months in ambient conditions, but the crispiness is reduced. Once removed from the containers, chips should be baked in a hot air oven to regain the crispiness before being packed into retail packages. This durian chip technology was developed by Chanthaburi's farmer housewife groups.

5.10.4 Durian paste

Durian paste is the most widely made processed durian across South-East Asia. This product is made from fully ripe durian aril, mixed with sugar and coconut milk or with sugar alone, stirred over a low heat until thickened. The product can be stored for a long time in a sealed metal container. For retail packages it is often packed in clear plastic tubes (Plate IX F). It may be consumed directly as dessert or used as a stuffing in Chinese moon cake (Maneepun *et al.*, 1994; Paweenakarn *et al.*, 1992).

5.10.5 Durian flour and powder

Mature but unripe durian can also be processed into flour by slicing the pulp unit into 1 mm thick slices, drying at 50–55°C for 17 h to about 7% moisture content, then crushing into powder. Durian flour contains 6.7–10.3% fat, 5.2–6.7% protein, 23.5–53.3% starch, 17.5–22.4% sugar, 2.6–4.4% soluble dietary fiber and 5.7–13.55% non-soluble dietary fiber. Durian powder can also be made by mixing durian pulp with water, homogenizing and filtering through wire mesh to remove fiber, then drum drying at 130°C to attain 5% moisture content. Flour from durian seeds can also be made in a similar procedure. This flour and powder can be used to make many products including ice-cream, crisp crepes, noodles, milk, pies, cookies, cakes, mussel chowder, cream and other local products (Anon., 1997; Haruthaithanasan, 1986).

5.10.6 Polysaccharide gel from durian rind

Durian rind contains high quantity polysaccharide gel consisting mainly of polygalacturonic acid. Polysaccharide gel extract from durian rind was found to have antibacterial properties (Maktrirat *et al.*, 2008). The extract has been formulated into dressing film used in animal wound healing treatments (Chansiripornchai *et al.*, 2005), into animal feed supplement to induce immune response in chickens (Chansiripornchai *et al.*, 2008) and into toothpaste and dental floss coating as an anti-cavity ingredient (Ariyawatcharin *et al.*, 2009).

5.11 Conclusions

As one of the most important fruit in South-East Asia, durian is now available around the world. However, its markets and consumption are still limited to the

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Asian population. Postharvest life of durian is still limited to about 2 weeks at 15°C due to its tropical origin and climacteric type fruit. Its high storage temperature allows the fruit to continue the ripening process and also the growth of various fungi. Its maturity determination procedure must be improved to separate fruit of different maturities, in order to handle each group correctly. The procedure must be based on many criteria and take the preharvest condition into account as well. Preharvest practices must be improved to obtain good quality fruit that will ripen evenly and be relatively free of pathogenic fungi. Fresh-cut durian will lead the market in the future due to the fruit's large size, low pulp to whole fruit ratio, uncertain aril quality, the growing cost of transportation and the fact that the aril can be stored at much lower temperatures than the whole fruit. Knowledge of nutritional and functional properties of durian is emerging and may encourage its consumption for other reasons than just being an exotic delicious fruit. Its offensive aroma will also be slowly overcome by the new hybrids and the relatively increased preference for the fruit among the non-Asian population.

5.12 Acknowledgements

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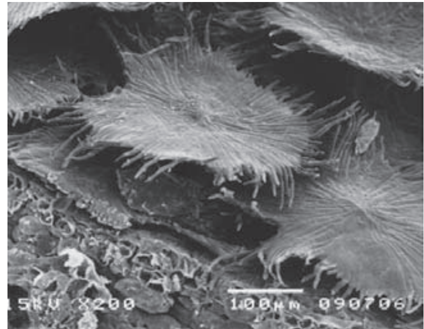
(a)

(b)

(c)



(d)

(e)

(f)

Plate VIII (Chapter 5) (a) durian fruit from well (left) and poorly (right) pollinated flowers; (b) the swelling around the abscission zone of durian stem; (c) durian pulp after dehusking; (d) peltate hair on durian spine (courtesy of S. Sangchote); (e) cross section of a durian fruit showing uneven iodine-starch staining of the aril; (f) dehiscence of a durian.

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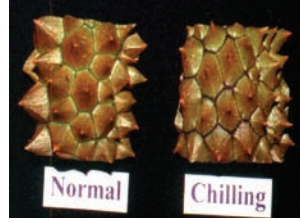
(a)

(b)



(c)

(d)

(e)

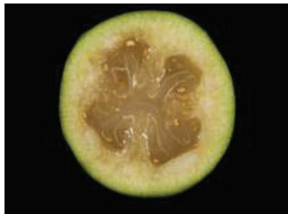
(f)

Plate IX (Chapter 5) (a) a cross section of a ripe Monthong durian fruit showing air space between the aril and the husk (notice that most seeds are aborted); (b) checking durian maturity by determining dry matter of the aril using a microwave oven; (c), a chilling injury symptom on durian husk; (d) *Phytophthora* rot on a durian fruit; (e) a durian dehusking tool (courtesy of S. Seehawong); (f) durian paste on display shelf.

(a)

(b)

(c)


(d)

(e)

Plate X (Chapter 6) Ripening index for feijoa fruit (a) seed pulp half white, half clear; (b) all of seed pulp area clear, (c) all of seed pulp area clear, but darkening (greyish); (d) seed pulp is completely brown, (e) seed pulp and flesh are brown. (a)–(b) mature fruit – for fresh consumption; (c) fruit for processing; (d)–(e) late senescence (developed by The New Zealand Institute for Plant & Food Research limited, Mt Albert, New Zealand).

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6

Feijoa (*Acca sellowiana* [Berg] Burret)

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Abstract: Feijoa is a climacteric fruit that needs to remain on the tree up to the point of natural fruit drop to attain its typical texture and strong aroma. Identifying horticultural maturity is difficult and mixed maturities at harvest can cause significant problems in later storage because of heterogeneity. Feijoas can be stored for up to four weeks at 4°C depending on the cultivar, with the end of storage life predominantly determined by flavour loss and internal browning. External changes during storage are limited except for shrivelling due to water loss, a slight change in flesh colour and appearance of symptoms resulting from bruising during harvesting and postharvest handling. The main storage disorders reported are chilling injury and CO_2 damage.

Key words: *Acca sellowiana, Feijoa sellowiana*, goiabeira serrana, aromatic, postharvest.

6.1 Introduction

6.1.1 Origin, botany, morphology and structure

The feijoa (*Acca sellowiana* [Berg] Burret, synonym *Feijoa sellowiana*) is a small evergreen shrub in the plant family *Myrtaceae*, genus *Acca*. The fruit of feijoa are highly flavoured and have a green skin with a heavy wax bloom and inside creamy coloured flesh with translucent seed pulp (Thorp, 2008). Other common names for feijoa are 'goiabeira serrana' in Brazil, 'guayabo del pais' in Uruguay and pineapple guava in mainland USA.

Feijoa is native to southern Brazil and Uruguay, where it can be found in association with the temperate araucaria forest dominated by the *Araucaria angustifolia* and the remnants of the forests where araucaria trees have receded and given place to natural grasslands (Ducroquet *et al.*, 2000; Thorp and Bieleski, 2002; Santander and González, 2007).

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Two distinct populations of feijoa have been identified (Thorp, 1988; Ducroquet *et al.*, 2000; Thorp and Bieleski, 2002). The 'Brazilian' type, found in higher altitude regions of the basalt plateau of south-eastern Brazil, has fruit with large seeds and relatively hard, often bitter flesh with consumers preferring to eat just the sweet, translucent seed pulp. The 'Uruguayan' type, found in the crystalline (acidic) soils of Uruguay and the south of Rio Grande do Sul state in southern Brazil, has fruit with small seeds and soft, sweet, juicy flesh that is consumed along with the seed pulp.

The Uruguayan fruit type is the one that has been commercialized around the world. Trees from Uruguay were first introduced to Europe by the French botanist and horticulturist, Dr Edouard André, in 1890 (André, 1898). It was first collected in southern Brazil by a German explorer, Freidrich Sellow, in 1815 and named after him and a Brazilian botanist, Joam da Silva Feijo.

The plant is a perennial shrub or small tree that naturally grows to a height of 4–6 m with pale grey-brown bark and spreading branches resulting in an irregular round canopy. The root system is fibrous and shallow. The leaves are thick and leathery, 3–7 cm long and 1.5–4 cm wide, glossy green on the upper surface and the lower surface is densely lanate with silver grey or brown hairs (Landrum, 1986).

The plant fruits in three to five years from seed, flowering in spring. The bisexual flowers are conspicuous, about 3–4 cm across and borne singly in the axil of leaves towards the base of the current season's shoot growth. The flower is epigynous, which means the ovary and fruit develop below the flower. Each flower produces several bright red stamens and usually a single red stigma, surrounded by four to six fleshy, edible petals that are white on the outside and red on the inside.

The fruit ripens in autumn; from March to June in the Southern Hemisphere and from October to December in the Northern Hemisphere. The fruit are ellipsoid to obovoid or ovoid in shape, 40–150 grams in weight on average, 2.5–13 cm long and about 2.5–6 cm wide, with persistent calyx segments adhering to the apex (Fig. 6.1). The fruit skin is green to dark green, covered in a wax bloom and may have a smooth or rough appearance. Spherical oil glands are present in the subepidermal region of the mesocarp, just below the epidermis. The mostly edible flesh is creamy-white and granular because of the presence of sclereids that develop in the outer parenchymatous region during fruit growth (Esemann-Quadros *et al.*, 2008). Numerous (20–40) small, round, flattened seeds are embedded in a jelly (seed pulp) located in a central cavity made up of three to five locules. As the fruit develops, the seed pulp turns from white to clear ('locule clearing'), to brown, then to dark brown followed by darkening of the pericarp tissue and finally the skin. (See Plate X in the colour section between pages 274 and 275.) The optimal stage of ripening for consumption depends on both personal/cultural taste (e.g. sugar/acid ratio) and cultivar (where some cultivars lose acidity earlier in the ripening process). The fruit have a unique flavour and are very aromatic with sweet subtropical fruit flavours reminiscent of strawberry, pineapple and guava.

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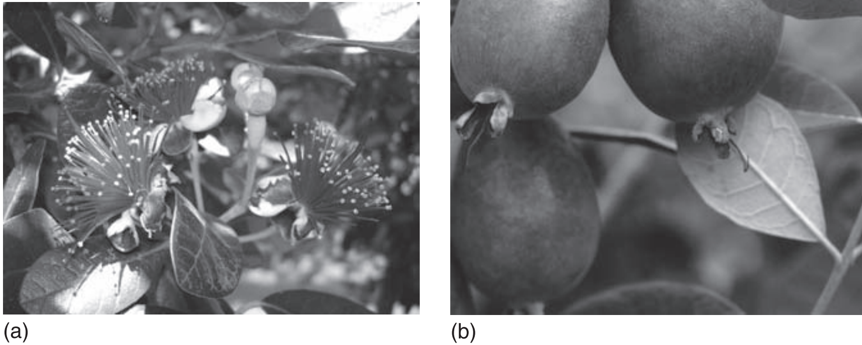

Fig. 6.1 (a) The feijoa flower and (b) mature fruit on the tree (with permission from Thorp and Bieleski, 2002).

Although feijoas originate in warm temperate or cool-subtropical regions, the trees will be damaged by cold temperatures below −3° in summer and −8°C in winter (Stanley and Warrington, 1984). Frosts will also damage the ripening fruit, resulting in premature browning of the affected tissues. Hot and dry conditions during flowering can interfere with pollination and fruit set. Sharpe *et al*. (1993) suggested that plants require 100–200 hours of chilling below 7°C. However, depending on the type of climate, feijoa will react either to seasonal temperature changes or to changes in rainfall patterns, as experienced in Colombia (Fisher *et al.*, 2003).

Feijoas can tolerate a range of soil conditions, even surviving the highly acidic, nutrient-poor soils of their native regions. In New Zealand they can be grown in a wide range of soils, including heavy clay soils (poor drainage). However, in commercial practice, best results are obtained in fertile, well-drained slightly acidic (pH 6.0–6.5) sandy loam rich in humus (Morton, 1987; Thorp and Bieleski, 2002; Fisher *et al.*, 2003).

6.1.2 Worldwide importance and economic value

After first introducing feijoa to France in 1898, Edouard André was responsible for its spread to other European countries, and to North America, from where it

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was distributed to Australia and New Zealand (Thorp and Bieleski, 2002). Distribution within South America is less certain, but plantings established in regions outside of Brazil and Uruguay are based on the same Uruguayan fruit type first introduced to France by André. Feijoa trees are now a popular home-garden tree in many countries but significant commercial production is now limited to New Zealand, Georgia, Azerbaijan, Colombia and California, although there is rapidly developing interest in establishing commercial production in Uruguay and Brazil (dos Santos *et al.*, 2009).

Commercial production of feijoas in New Zealand is located throughout the North Island and upper regions of the South Island. In 2008, about 200 growers were active on 251 ha producing 500 tonnes of fruit per year, representing a value of €853 126 in domestic sales and €50 184 in export sales, mainly to Australia and California (Aitken and Hewett, 2008). Local production in California is located mainly in southern regions around Los Angeles and San Diego but there are only 10 small commercial growers active, with total commercial sales being 23–34 tonnes of fruit (John Swift, personal communication). In Georgia and Azerbaijan, feijoas are grown in subtropical regions protected by the Caucasus Mountains to the north and adjacent to the Black Sea and Caspian Sea. It has been reported there are 1000 ha producing 1200 tonnes of fruit in Georgia and 900 ha producing 1600 tonnes in Azerbaijan. There are 450 ha of feijoas established in Colombia, with the main commercial areas located in the Caldas region where there are 20 growers cultivating an area of 133 ha producing 2000 tonnes per year (Fisher *et al.*, 2003; Gallego-Corrales *et al.*, 2003).

6.1.3 Cultivars and genetic variability

The development of high quality, large fruited, feijoa cultivars has been mainly limited to New Zealand, but more recently new cultivars are also being produced in Colombia and Brazil. The main commercial cultivars in New Zealand are all based on the Uruguayan fruit type with soft juicy flesh and small seeds (Thorp and Bieleski, 2002; Anon., 2008):

- early season: ‘Anatoki’, ‘Gemini’, ‘Kaiteri’, ‘Kakariki’, ‘Pounamu’, ‘Unique’
- mid season: ‘Apollo’, ‘Den’s Choice’, ‘Kakapo’, ‘Mammoth’
- late season: ‘Opal Star’, ‘Triumph’, ‘Wiki Tu’.

Progeny from New Zealand has also been used by Colombian researchers to develop cultivars adapted to the environmental conditions in Colombia, resulting in the selection of ‘Quimba’ (clone 41) and clone 8–4 (Rodríguez *et al.*, 2006). There has been less development of germplasm based on the Brazilian fruit type but recently several cultivars were released by Epagri in Santa Catarina, Brazil (Ducroquet *et al.*, 2007; Ducroquet *et al.*, 2008). The main characteristics targeted during breeding included self-fertility, consistently high yields of evenly sized fruit, smooth skin, low grittiness, good flavour and long storage life.

Practically all physiological studies of feijoa, pre- and postharvest, will have been based on the Uruguayan fruit type, but Amarante *et al.* (2008) compared the

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two types and found that they have similar behaviour. It will be important to increase our knowledge of the pre- and postharvest behaviour of the Brazilian fruit type.

6.1.4 Culinary uses, nutritional value and health benefits

Feijoas are versatile fruit that can be used in a variety of ways. Although best eaten fresh, feijoas can be processed into pieces or puree and incorporated into bakery products, sauces, pies, or drinks and still retain their typical highly aromatic flavour. Commercially available processed products with feijoa as flavouring include juices, jams, wine, vodka, ice cream, yoghurts, breakfast cereal and chocolates.

The fruit are rich in vitamin C, fibre, ascorbic acid, potassium, phosphorous, magnesium, sugars and calcium (Table 6.1). A full mineral analysis of the fruit is provided by Leterme *et al.* (2006). Feijoas contain high amounts of bioflavonoids or vitamin P, (P)-active polyphenols, such as catechin, leucoanthocyanins, flavonols, proanthocyanidins and naphthoquinones (Ielpo *et al.*, 2000). Several authors found potent antimicrobial activity against Gram-positive and Gram-negative bacteria as well as fungi (Basile *et al.*, 1997; Vuotto *et al.*, 2000). Additionally, Vuotto *et al.* (2000) stated that feijoa could be a source of

Table 6.1 General feijoa fruit facts

Parameter	Range
Number of seeds	20–40
Diameter (cm)	2.5–5
Length (cm)	2.5–13
pH	3.2–4.4
Soluble solids content (%Brix)	10–16
Acidity (g malic acid 100 g^{-1} FW)	0.80–1.60
Moisture (%)	84–89
Proteins (%)	0.50–1.2
Fat (%)	0.05–0.4
Glucose+Fructose (%)	0.6–3.0
Sucrose (%)	2.5–7.5
Fibre (%)	3.8–5.0
Ash (%)	0.20–0.40
Vitamin C (mg 100 g^{-1} FW)	25–36
Iodine (mg 100 g^{-1} FW)	3
Sodium (mg 100 g^{-1} FW)	0–9
Potassium (mg 100 g^{-1} FW)	90–170
Calcium (mg 100 g^{-1} FW)	4–15
Magnesium (mg 100 g^{-1} FW)	5.8–9.0
Iron (mg 100 g^{-1} FW)	0.0–0.4
Phosphates (mg 100 g^{-1} FW)	10–17

Sources: Visser and Burrows (1983), Romero-Rodriguez *et al.* (1994)

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antibacterial, antioxidant, anti-inflammatory and, perhaps, antimutagenic agents. Finally, feijoa have been reported to have anti-cancer properties (Nakashima, 2001; Bontempo *et al.*, 2007) and to influence cytokine secretion in the intestine (Manabe and Inobe, 2005). Ebrahimzadeh *et al.* (2008) provide data of the total phenol content, flavonoid content and Fe^{2+} chelating activity of both feijoa fruit and leaves.

Few traditional uses of feijoa have been documented. Fruit collected from the wild in their centres of origin in Brazil and Uruguay are generally small and in poor condition. In traditional communities the fruit are more commonly used for medicinal purposes and as candy rather than consumed as fresh fruit (dos Santos *et al.*, 2009). The flower petals may also be consumed (dos Santos *et al.*, 2009) and an infusion, made from the leaves or fruit skins, is sold in homeopathic pharmacies and used as a cure for dysentery.

6.2 Preharvest factors affecting fruit quality

6.2.1 Flowering and pollination

Individual feijoa flowers are open for one to two days, but the flowering period on a tree may continue for four to six weeks. The flowers are hermaphroditic, meaning the male pollen and the female ovules are produced within the same flower. However, the two are generally self-incompatible and the flower is generally self-sterile even though pollen germination and pollen tube growth take place (Dettori and Di Gaetano, 1991). Only the cultivar 'Unique' is self-fertile. Flower formation and subsequent fruit set can be markedly improved by applying potassium phosphate to improve phosphate availability (Garcia *et al.*, 2008).

The flowers do not produce any nectar and therefore are not particularly attractive to bees. Additionally, the insects collecting pollen do not transfer as much pollen to stigmatic surfaces as birds do (Stewart and Craig, 1989). These birds are attracted by the brightly coloured flowers to feed on the sweet and juicy petals. In New Zealand and California, the main pollinators for feijoa are blackbird (*Turdus merula*) and mynahs (*Aceridotheres tristis*). Birds of a similar size to these, from the Muscicapidae, Turdidae and Thraupidae (sub)families, are also known to be the best pollinators for feijoa in their native habitats in Uruguay and Brazil (Ducroquet and Hickel, 1997) as well as in Colombia (Fisher *et al.*, 2003).

Feijoas generally suffer from high rates of flower and fruit abortion, and as a result fruit set is limited to 30% with open pollination (Thorp and Bieleski, 2002). Fruit set appears to be dependent on the flower morphology (Degenhardt *et al.*, 2005) and may be improved by treatments with ethephon (Garcia *et al.*, 2008). Additionally, fruit yield tends to be larger from earlier bloom dates and these fruit are also larger and contain more sugars than those from later bloom dates (Harman, 1987).

When only a few ovules in the ovary are fertilized, a fruit may still develop but it will be small, misshapen and unmarketable, or the fruit may reach a marketable size but will be hollow inside with little or no edible pulp and with dry flesh. Hand

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pollination achieves nearly 100% fruit set, producing larger fruit containing more seeds (Patterson, 1989). Hand pollination also results in a six-day reduction in the time for the fruit to reach full maturity.

6.2.2 Fruit growth and development

Once the flower is adequately pollinated, the fruit starts to grow within a few weeks of flowering, with the actual time varying according to cultivar (Thorp and Bieleski, 2002). The first visible signs of fruit growth occur when shoot growth slows down and the unpollinated and poorly pollinated flowers have been shed. In general, fruit growth follows a sigmoidal curve with three distinct stages. In the first stage (20–70 days after anthesis (DAA)), fruit growth is linear; in the second stage (70–95 DAA), growth rate declines but in the third and final stage (>95 DAA) growth accelerates up to the point of fruit drop (horticultural maturity) at between 80 and 140 DAA depending on cultivar and environment (Harman, 1987; Rodríguez *et al.*, 2006).

The sugar content of feijoa fruit starts to increase about 80 DAA, from 0.56% of fruit fresh weight (FW) and reaches about 4% of FW at horticultural maturity (Harman, 1987). Fructose and glucose make up most of the sugar during the development of the fruit, but at 90–100 DAA sucrose levels start to increase and sucrose becomes the dominant sugar when the fruit is fully ripe. Starch content remains low but constant (0.6–1.5% of fruit dry weight (DW)) during fruit development which suggests that sugars increase because of translocation from the leaves via phloem or via the xylem from carbohydrates stored in the wood, rather than from starch to sugar conversion. However, Rodríguez *et al.* (2006) noted a modest increase in starch content during final maturation (112–150 DAA). Organic acid content (malic + citric) increases from 1–1.7% DW at 90 DAA up to >12% DW at 120 DAA (Harman, 1987). Total contents of calcium, magnesium and potassium per fruit all increase as the fruit grows but their concentration does not. As calcium and magnesium are relatively immobile in plants, their concentration declines initially (40–80 DAA) and remains constant thereafter. Potassium concentration is fairly constant overall during the entire fruit growth period and is still accumulating in the fruit at the time of natural fruit drop.

During the maturation stage, the textural characteristics of the pulp will also change because of the action of hydrolases on the cell wall and more specifically the pectin embedded in them. This is also reflected in an increase of the activity of polygalacturonase during maturation and later ripening. This activity is higher in the centre of the mesocarp, which is consistent with the fruit softening from the inside out (Fisher *et al.*, 2003). Cellulases also play a role in the softening of the fruit, evidenced by the noticeable increase in activity during maturation.

As for many other fruit, the aroma and typical flavour are the last to develop. 15 (Shaw *et al.*, 1990) to 57 aroma components were identified (Shiota *et al.*, 1980) which include terpenes, tannins, quinones, steroidal saponins, methyl- and ethyl-benzoate (Binder and Flath, 2002). The latter two (methyl-benzoate and

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ethyl-benzoate) are determining for the typical feijoa aroma (Hardy and Michael, 1970; Shiota *et al.*, 1980; Shaw *et al.*, 1989; Shaw *et al.*, 1990). Measurement of sequential changes in the aroma profile following natural abscission of the fruit suggested that ethyl-benzoate concentrations may be useful in the determination of optimum ripeness (Sharpe *et al.*, 1993).

6.2.3 Maturity and harvest

Maturation of fruit on the plant to the point of horticultural maturity is difficult yet important to identify, especially with feijoas. Fruit maturation occurs with the coordinated subtle compositional changes previously discussed, along with very subtle reductions in firmness and skin hue angle (less green, more yellow) (Clark *et al.*, 2005) and optimal eating maturity is generally reached 120–140 DAA (Harman, 1987). In general this stage coincides with the moment of natural fruit drop (Thorp and Klein, 1987). Feijoas harvested prematurely do not fully develop their characteristic flavour and texture, while leaving the fruit too long on the tree will result in considerable losses from bruising as a result of natural fruit drop to the orchard floor. Consequently growers currently use a low retention force as the harvest maturity index. Fruit are removed with very little force, referred to as touch picking, and this relies on the strength of the abscission zone between the fruit and the stalk or the fruit retention force (Downs *et al.*, 1988). The fruit is gently tilted sideways or forward, gently pulling down and harvesting only if the fruit is released easily. There are important differences between cultivars with respect to the rate of ripening relative to fruit maturation and natural fruit drop. These need to be taken into consideration when developing maturity standards and determining time of harvest. Some cultivars such as ‘Apollo’ and ‘Unique’ can be harvested at a higher retention force as their optimum harvest maturity is reached a few days before natural fruit drop. Other cultivars like ‘Triumph’ must be harvested at a low retention force, close to the time of natural fruit drop, to give good fruit quality. In addition, some growers report differences in retention force (to achieve the same fruit maturity) both between and within seasons. Thus, it is generally recommended that pickers be well trained and their performance continually monitored (by cutting the fruit) to ensure fruit are being harvested at the correct maturity.

An alternative harvesting method is to use suspended catching nets (Fig. 6.2). This would result in harvest of fruit at the time of abscission whilst ensuring that the fruit are not damaged by contact with the orchard floor (Thorp and Klein, 1987). This could be carried out using either manual or mechanised tree shaking (similar to that used for mechanised olive harvesting). It should be noted that this attribute of feijoa makes it an excellent candidate for orchards dedicated to growing fruit for processing.

In addition to assessment of crop maturity to decide on harvest timing, heterogeneity of fruit that are present on a tree at harvest is a major challenge for the industry. This issue is best approached by using cultivars with more consistent fruit shape, by improving pollination systems and by removing small and poorly

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Fig. 6.2 Modern feijoa orchard with suspended catching nets and wind barriers to prevent wind damage (courtesy of Grant Thorp).

pollinated fruit within six weeks of anthesis (Thorp and Bieleski, 2002). In New Zealand and the Northern Hemisphere, where there are clear seasons, feijoa fruit may be harvested over a period of three to four months during late summer and autumn, with the main crop of fruit from any individual cultivar being mature and ready for harvest over a two- to three-week period. In Colombia, trees produce year round with a six to eight-month peak harvesting period coinciding with their wet season (Fisher *et al.*, 2003).

6.2.4 Yield

In New Zealand, mature feijoa trees can produce 30–40 kg of fruit (22 tonnes per ha) but depending upon the cultivar and success of pollination, only 30–50% of the fruit harvested meet commercial size and quality standards. In Colombia, production can be much higher, reaching 12 tonnes per ha per month (Fisher *et al.*, 2003).

Crop regulation and selective fruit thinning can do a great deal to improve commercial packouts by removing small and misshapen fruit. This approach will also improve harvesting and packing operations by removing most of the reject fruit at an early stage, before they can interfere with the main harvest. The alternative to thinning fruitlets is to thin flowers, but reducing flower numbers produces real benefits to the grower only if the remaining flowers are hand pollinated.

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6.3 Postharvest physiology and quality

6.3.1 Respiration and ethylene production

Feijoa is a climacteric fruit, producing approximately 0.2 nmol C_2H_4 $kg^{-1}s^{-1}$ at harvest and up to 0.6 nmol C_2H_4 $kg^{-1}s^{-1}$ at the climacteric maximum at 20°C, with the corresponding rise in CO_2 production rate a few days later from 654–1000 nmol CO_2 $kg^{-1}s^{-1}$ (climacteric minimum) to 880–1600 nmol CO_2 $kg^{-1}s^{-1}$ (climacteric maximum) (Gallego-Corrales *et al.*, 2003; Amarante *et al.*, 2008). Rates of respiration respond to temperature change within the range of 0–30°C linearly (Gallego-Corrales *et al.*, 2003), with a Q10 of 3.4–3.5 (Amarante *et al.*, 2008). Respiration rates at the recommended storage temperature of 4–5°C tend to be in the range of 120–200 nmol CO_2 $kg^{-1}s^{-1}$ (East *et al.*, 2009).

6.3.2 Ripening, quality components and ripening indices

The ability to identify varying maturity/ripeness is one of the major challenges that inhibits delivery of a consistent quality and hence retards the development of commercial industries (Vela *et al.*, 2009). This is especially important with feijoas where it is common to find substantial variability in ripening rates and storage performance within the same commercial lines of fruit because of mixed maturities and inherent difficulties when harvesting by touch picking fruit.

Feijoas ripen from the inside out and as fruit become over-ripe there is first of all a loss of flavour (reduced soluble solids concentration and titratable acidity) and browning in the seed pulp, followed by more flavour loss and browning of the flesh (Klein and Thorp, 1987). External quality changes that occur during postharvest ripening are not dramatic, making it difficult to ascertain maturity/ripeness of any fruit by eye, touch or other non-destructive techniques. Non-destructive techniques that have been trialled include density sorting (Gaddam *et al.*, 2004; Clark *et al.*, 2005) stiffness or acoustic impulse (Gaddam *et al.*, 2004; 2005) and fruit retention force required during harvest (Downs *et al.*, 1988). At this stage, without reliable non-destructive techniques, postharvest ripening changes are best ascertained by observing the state of the seed pulp. Within an immature fruit the locules contain firm, white seed pulp; in a ripe fruit the seed pulp becomes translucent (locule clearing) and in over-ripe feijoa the seed pulp is brown and with little of the characteristic feijoa flavour and generally low acidity. These characteristics were used in New Zealand to develop a ripening index (Plate X). An instrumental method of assessing seed pulp colour change in the locules, based on black and white conversion of scanned feijoa halves, developed by Wiryawan *et al.* (2005), may prove useful for reducing error when assessing fruit ripeness. Additionally, the stiffness showed a good correlation with the ripening index and might prove to be useful in the future (Gaddam *et al.*, 2005).

During cool storage and subsequent shelf life at room temperature, not all quality attributes change at the same rate. Flavour is the first characteristic to change noticeably and this is associated with the slow decrease in titratable acidity

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and higher pH that are consistently reported, and possibly a decrease in sugars (measured as soluble solids content, SSC), although changes in SSC appear to be irregular with no changes in SSC reported just as commonly as a decrease or increase (Klein and Thorp, 1987; Gallego-Corrales *et al.*, 2003; Gaddam *et al.*, 2005; Rodríguez *et al.*, 2006; Al-Harthy *et al.*, 2008; Velho *et al.*, 2008; Al-Harthy *et al.*, 2009a; 2009b). Reduction in firmness and slight yellowing of the skin (reduced hue angle) are typically reported during storage (Akerman *et al.*, 1993; Gallego-Corrales *et al.*, 2003; Al-Harthy *et al.*, 2008) with rates of loss of hue angle more rapid at higher storage temperatures (Amarante *et al.*, 2008).

Reported rates of weight loss for polylined packaged fruit range from 0.75% (Al-Harthy *et al.*, 2008) to 1.25% (Hoffman *et al.*, 1994) per week at low storage temperatures (0–4°C). Weight loss without polyethylene bag protection or at ambient storage conditions can be as high as 5.5% of initial fruit weight per week (Hoffman *et al.*, 1994; Rodríguez *et al.*, 2006). Water vapour permeance of the skin (i.e. water loss through the skin) is within the range of 4–8 nmol s^{-1} m^{-2} Pa^{-1} (Wiryawan *et al.*, 2005).

6.4 Postharvest handling factors affecting quality

6.4.1 Handling and grading

Feijoa are generally graded for size using a mechanical grader (Fig. 6.3) with the grading standards depending on the country (Table 6.2). At this time, misshapen and blemished fruit will also be removed manually. Fruit are generally packed into plastic pocket packs and placed inside polyethylene-lined single layer trays. Polyliners are not necessary for fruit stored for short periods but they are essential

Fig. 6.3 Size grading of feijoa fruit. (Courtesy of Grant Thorp)

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Table 6.2 Feijoa grading standards in Colombia

Parameter	Range		Class
Weight (g)	> 80		Select (Selecta)
	60–80		Current (Corriente)
	40–59		Middle (Mediana)
	<40		Small (Pequeña)
Size (height (h) and diameter (d))	> 75 (h)	> 38 (d)	First (Primera)
	66–75 (h)	31–38 (d)	Second (Segunda)
	< 66 (h)	< 31 (d)	Third (Tercera)

Source: Fisher *et al.* (2003)

to prevent excessive weight loss and fruit shrivelling during long-term storage. However, polyliners are likely to lead to an increase in rot incidence.

6.4.2 Temperature and relative humidity

The recommended storage temperature range for feijoa is between 5°C and 10°C in Colombia, whereas a lower temperature of 4–5°C is used in New Zealand. At 4°C, the main commercial cultivars in New Zealand ('Apollo', 'Gemini', 'Opal Star', 'Pounamu' and 'Triumph') generally have a commercial storage life of four weeks, with a maximum of five days' subsequent shelf life at 20°C before fruit become unacceptable in terms of flavour and internal browning of the seed pulp (Thorp and Bieleski, 2002). Fruit of 'Unique' have a much reduced storage life, developing flesh browning after seven days. A high relative humidity (90–95%) is recommended in cool stores to avoid water loss during storage, in addition to the use of polyliners in the cardboard packaging.

6.4.3 Modified or controlled atmosphere

Controlled atmosphere (CA) storage can be used to extend the storage life of feijoa fruit (Thorp and Bieleski, 2002). In preliminary work, ripening was delayed both during cold storage and during subsequent shelf life at room temperature, when fruit were held in a range of low O_2/low CO_2 atmospheres. Treatments included air storage; 2.0% CO_2; 5.0% CO_2; 2.5% CO_2 with 2.0% O_2; 5.5% CO_2 with 2.0% O_2. Low O_2 and zero CO_2 atmospheres were best, as fruit were damaged by CO_2 at the low concentrations of O_2 being tested. Symptoms of carbon dioxide damage were localized regions of brown, dry cortical tissue in the outer flesh of cut fruit.

East *et al.* (2009) found that among a matrix of 16 atmospheres tested, those with low (0–3%) CO_2 in combination with low (3%) O_2 provided the best fruit outcomes at the completion of storage, yet quality benefits were only modest in comparison with the quality of fruit stored in air. Fruit stored in atmospheres with relatively high (7%) CO_2 tended to soften faster, have more seed pulp browning and contain more injuries than air-stored fruit. Subsequent studies found similar

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results, including a reduction in the rates of change in the epidermal colour, seed pulp browning and defect incidence for 'Unique' fruit (Al-Harthy *et al.*, 2009a), with the best atmospheres being 0% CO_2 in combination with 2–5% O_2.

A 24-hr anaerobic treatment (98% N_2) before storage has been trialled, with some success, in order to increase volatile production (Pesis *et al.*, 1991).

6.4.4 Ethylene

The presence of ethylene in the storage environment may have a limited effect on advancing the ripening of the fruit. Akerman *et al.* (1993) found that application of 100 ppm for 96 hrs at 22°C caused increases in both respiration rate and ethylene production. Exogenous application of 66 ppm for 24 hours caused no changes in ethylene production and respiration rates, but resulted in advanced darkening of the locule material while reducing skin browning during a subsequent two weeks at 23°C (Velho *et al.*, 2008).

Treatment of Brazilian-type fruit with 1500 ppb 1-methylcyclopropene (1-MCP, SmartFresh™) for eight hours at 20°C before cool storage at 4°C resulted in quality maintenance that produced significantly superior fruit after 30 days of storage (but not after 15 days) (Amarante *et al.*, 2008). For 'Apollo' (Uruguayan type), ripening (non-stored) was not slowed down, nor were fruit firmness or ripening effects (five weeks at 4°C) noted from use of either 500 or 1000 ppb 1-MCP (White and Woolf, unpublished data). Application of 1-MCP at 1 ppm for 24 hours caused no dramatic changes in physiology (respiration rate and ethylene production) and only reduced reduction in loss of hue angle (among many quality attributes measured) during two weeks of shelf life at 23°C (Velho *et al.*, 2008).

6.5 Postharvest crop losses

6.5.1 Chilling injury

Feijoas will develop chilling injury (CI) after prolonged storage at low temperatures (Klein and Thorp, 1987; Gallego-Corrales *et al.*, 2003). Symptoms of CI include browning of the vascular bundles at the stem end of the fruit, which, with increased severity, becomes visible externally as brown and sunken skin tissue. In some cultivars, another expression of CI can be a diffuse pink/reddish colouration of flesh (see Plate XI in the colour section between pages 274 and 275). The severity of damage is cultivar dependent and related to length of time in storage, since even long periods at 4°C may still induce off flavours related to CI. Even mild CI can result in the early development of off flavours. Cultivar differences in susceptibility to 0°C have been observed, where 'Apollo' was much more tolerant than 'Opal Star' (incidence of vascular browning after five weeks of storage at 0°C was 4% and 68%, respectively).

Several conditioning techniques have been investigated to overcome CI while storing at very low temperature (Woolf and White, unpublished data). Treatments evaluated included low temperature conditioning, step-down temperature

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management and hot water treatments; none of these showed any significant benefit in terms of longer storage life. The principle of low temperature conditioning is to expose fruit for relatively short periods to temperatures slightly above the temperatures that induce CI during long-term storage. However, for 'Gemini', temperatures of 12, 9 and 6°C for three or six days before storage at 0°C for three or five weeks did not reduce chilling symptoms. Step-down temperature regimes, where fruit are stored at progressively lower temperatures as the time in storage increases (≅ 1°C each week over the storage period), were also evaluated. 'Apollo', 'Gemini', 'Opal Star' and 'Unique' were stored for five weeks under three temperature regimes: 4°C (standard storage temperature), 0°C (low temperature that induces CI), and step-down (1°C drop each week, i.e. 4°C, 3°C, 2°C, 1°C and 0°C for a week each). Fruit stored at 0°C had ripened less, but showed significant symptoms of CI. Fruit exposed to step-down storage had no CI, but was not significantly less ripe than fruit stored at a constant 4°C.

Hot water treatments (34 to 55°C) applied to 'Triumph', 'Opal Star', 'Unique' and 'Apollo' fruit before storage at 0°C (chilling inducing), or 4°C (standard storage temperature) did not slow down ripening at 4°C, nor was CI at 0°C reduced. Additionally, feijoa appeared to be very sensitive to the hot water treatment, with damage observed at temperatures as low as 34°C. Additionally, 1-MCP application (24 hours at 500 and 1000 ppb) to 'Apollo' fruit did not reduce CI at 0°C for three or five weeks (White and Woolf, unpublished data).

6.5.2 Physical damage

Bruising is the most common cause of fruit damage during postharvest handling of feijoas. It can result in serious internal damage to fruit during storage even though there are no apparent external signs at harvest or packing (Thorp and Klein, 1987). Damage from bruising is more visible in fruit with soft flesh (e.g. 'Apollo') than it is with fruit that have relatively firm flesh at harvest (e.g. 'Triumph'). Bruised fruit ripens prematurely and unevenly, with the pulp adjacent to the point of impact becoming over-ripe before the rest of the fruit, causing off flavours to develop. Bruising damage is difficult to identify in intact feijoa fruit. Often there are no visible external signs of damage at the point of impact even after long-term storage.

Another type of physical damage often seen is wind damage, but this is a purely cosmetic problem and does not affect the internal quality of the fruit nor does it affect postharvest storage. However, it is a common cause of fruit rejection for export. This type of damage occurs in the orchard because of rubbing of leaves against the fruitlets or later rubbing of the fruit against branches. This is dealt with by correct pruning, incorporating natural wind screens and special training systems (Fig. 6.2).

6.5.3 Other physiological disorders

The flesh of different cultivars turns brown at different rates. The process is related to the activity of polyphenol oxydase (PPO). Fruit of 'Gemini' and 'Marian' have

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low levels of PPO activity and show little internal browning during storage, while 'Apollo' fruit have higher levels of PPO activity and show more browning. Lower temperatures have been used in conjunction with a calcium dip treatment to maintain firmness and delay the onset of browning.

6.5.4 Pathological disorders

Anthracnose (*Colletotrichum gloeosporioides*) causes significant fruit losses both in the field, while fruit are still attached to the tree, and postharvest (Ducroquet *et al.*, 2000; Fisher *et al.*, 2003). There is a wide range in susceptibility among the wild germplasm, which researchers in Brazil are utilizing to develop new, more resistant cultivars. Other fruit rots, such as *Botrytis cinerea, Penicillium* spp. and *Pestalotia* spp. can develop during storage, but usually after the internal quality of the fruit has deteriorated. In New Zealand, there are few problems with postharvest diseases generally not requiring fungicide treatment. Tentative identification of pathogens from storage rots in New Zealand includes: *Botrytis*, *Colletotrichum acutatum*, *C. gloeosporioides*, *Pestalotiopsis*, *Penicillium* sp., *Cylindrocladium* sp., *Fusarium*, *Phomopsis*, *Botryosphaeria* spp. (Rheinlander, Andersen, Manning, Meier and Woolf, unpublished data).

6.5.5 Insect pests and their control

In general, feijoa is a relatively pest-free crop that can be grown organically, even in temperate environments. Although they generally do not grow in fruit fly-infested areas, they are attractive to fruit flies (*Anastrepha sp.*, *Ceratitis capitata*), which can cause problems for export of fruit (Fisher *et al.*, 2003). Fruit fly can be controlled using dimethoate or fenthion dipping or flood spraying or using methyl bromide fumigation, but none of these are accepted in organic production. Similar export problems can be caused by oribatid mites in New Zealand, but these can be removed successfully by air blasting the fruit after harvest. Other possible problems can include mealybug, leafrollers, thrips, scale and Guava moth. There is no label treatment for methyl bromide for mealybugs on feijoa. Therefore, if pests are intercepted, the consignment is destroyed or redirected.

Cold quarantine treatment (e.g. 1°C for 12–14 days for fruit fly) is likely to cause chilling symptoms in many cultivars. However, some success has been shown in Colombia with a quarantine treatment (T–107–b) of 1.67°C for 22 days, which did not noticeably affect the fruit (Valderrama *et al.*, 2005).

6.6 Processing

There are many opportunities for processing feijoa, as the distinctive flavour of the fruit has been found to be relatively stable with processing. Commercially available processed products with feijoas as flavouring include juices, fruit

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blends, jams, alcoholic beverages, dairy products (ice creams and yoghurts), cereal products, bakery products, confectionery and chocolates.

One key decision in feijoa processing is whether to remove the green 'skin' before processing. While the outer flesh contains a high proportion of the characteristic feijoa flavours (Shaw *et al.*, 1989), it also contains bitter and sour flavours that can be imparted to the final product. Apart from the green colour there is no clearly defined skin on a feijoa to differentiate it from the pericarp, so it is difficult to decide when peeling has been completed and how much of these bitter and sour flavours have been removed. Peeling feijoa on a commercial scale is also difficult because of the large variance in the size and shape of the fruit (exacerbated by the fact that only lower quality fruit are processed) and the relative softness of highly mature fruit. The most common peeling methodology currently used is abrasion peeling of pre-frozen fruit. Freezing the fruit prior to peeling increases the hardness of the fruit and hence ensures that the abrasion process results in whole peeled fruit. Up to 80% of the fruit can be retained when using this method. Other peeling techniques that have been trialled with some success include heat; lye; enzyme and vacuum peeling techniques (Finlay, 2001).

Browning of processed feijoa products during subsequent storage can be a problem. In minimally processed products with low water activity, non-enzymatic (Maillard) browning is possible, while products that significantly deform the fruit (i.e. purees and juices) can be subjected to enzymic browning as a result of the release of polyphenoloxidase. Inhibition of the action of this enzyme can be achieved by heating to 90°C for approximately one minute (Wilson and Hoskin, 1986), storing at −15°C, or treating with sulphur dioxide.

6.7 Conclusions

Feijoas are a subtropical fruit with a very characteristic aroma that is loved by almost everyone who has a chance to eat them. There are two main genotype groups, the Brazilian fruit type and the Uruguayan fruit type, with the latter being the one that has spread around the world. This Uruguayan fruit type is the basis of the best known cultivars and consequently has been the fruit type most often used in fruit quality and postharvest research. However, recent postharvest research with fruit of the Brazilian fruit type has not shown any important differences between the genotypes, with internal browning of the seed pulp being the key determinant of quality for both fruit types.

Feijoa is a climacteric fruit but needs to remain on the tree up to the point of natural fruit drop to attain its typical texture and strong aroma. Developmental changes associated with fruit maturation and ripening occur very rapidly during the final stages of growth, so that at any one point there can be fruit at a wide range of development and maturity on any one tree. Additionally, the fruit does not show major external changes during maturation and ripening. These two factors make the determination of optimal harvest date problematic and currently the main maturity indicator used for harvest is retention force. Fruit from the main

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cultivars can be stored for four weeks at 4°C, with storage life determined by loss of flavour and internal browning of the seed pulp and flesh. The main storage disorders are water loss resulting in weight loss and shrivelling which can be solved by the use of polyliners; chilling injury which prevents storage at temperatures lower than 4°C; and CO_2 damage at the low levels of O_2 used in modified atmosphere storage.

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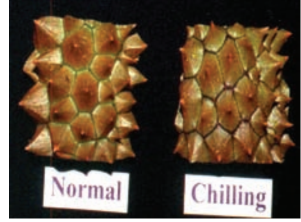
(a)

(b)



(c)

(d)

(e)

(f)

Plate IX (Chapter 5) (a) a cross section of a ripe Monthong durian fruit showing air space between the aril and the husk (notice that most seeds are aborted); (b) checking durian maturity by determining dry matter of the aril using a microwave oven; (c), a chilling injury symptom on durian husk; (d) *Phytophthora* rot on a durian fruit; (e) a durian dehusking tool (courtesy of S. Seehawong); (f) durian paste on display shelf.

(a)

(b)

(c)

(d)

(e)

Plate X (Chapter 6) Ripening index for feijoa fruit (a) seed pulp half white, half clear; (b) all of seed pulp area clear, (c) all of seed pulp area clear, but darkening (greyish); (d) seed pulp is completely brown, (e) seed pulp and flesh are brown. (a)–(b) mature fruit – for fresh consumption; (c) fruit for processing; (d)–(e) late senescence (developed by The New Zealand Institute for Plant & Food Research limited, Mt Albert, New Zealand).

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(a)

(b)

Plate XI (Chapter 6) Chilling injury in feijoa. (a) Internal symptoms include vascular browning and pink discoloration of the flesh; (b) external symptoms include longitudinal browning of the skin.

Plate XII (Chapter 7) Different stages of fig fruit development, externally and internally.

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7

Fig (*Ficus carica* L.)

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Abstract: The fig (*Ficus carica* L.), one of the first cultivated trees in the world, is grown in many parts of the world with moderate climates. Figs are eaten dry and fresh; however, as fresh figs are highly perishable they are largely consumed near production areas. Figs are nutritious fruits rich in fiber, potassium, calcium, and iron. Fresh figs are highly sensitive to physical damage, and susceptible to postharvest decay infections. Preharvest and postharvest conditions are very important to improve fruit quality and postharvest life. At this point, reducing postharvest losses and developing global fresh fig marketing is a big challenge for plant breeders, physiologists and postharvest technologists.

Key words: *Ficus carica*, fig, maturity stage, postharvest technology, antioxidants, shelf life, diseases.

7.1 Introduction

7.1.1 Origin, botany, morphology and structure

The genus *Ficus*, of the Moracea family, includes a large number of species (600–2000), with most found in the tropics or subtropics and only a handful with fruits considered edible (reviewed in Condit, 1969). The cultivated fig, *Ficus carica* L., is clearly of greatest importance as a source of human food and the only *Ficus* species cultivated for its fruit (Ferguson *et al.*, 1990). Fig trees are one of the first cultivated trees in the world (Solomon *et al.*, 2006), as acknowledged from records dating to the thirtieth century BC (Ferguson *et al.*, 1990). Although their origin is not entirely known, fig trees are thought to have originated in western Asia (Stover *et al.*, 2007a), 'in the fertile part of southern Arabia' (Ferguson *et al.*, 1990). Wild or 'nearly wild' figs are reported throughout much of the Middle East and Mediterranean region (De Candolle, 1886). Figs slowly

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extended through the Mediterranean region (Stover *et al.*, 2007a), and by the fifth century AD, figs had been distributed throughout the Mediterranean and along the Atlantic shores (Ferguson *et al.*, 1990). Interestingly, the fossil record shows a prehistoric distribution of *Ficus carica* across southern Europe (De Candolle, 1886). The ability of fig fruits to dehydrate facilitated fig distribution (Aksoy, 1998). Figs arrived in America in 1520, brought by the Spaniards, and in 1769 they were introduced to California from Mexico by the Franciscan missionaries. Today, figs are grown in many parts of the world with moderate climates (Obenauf *et al.*, 1978).

F. carica is a deciduous bush or tree of around 3–6 m in height (Crisosto and Kader, 2007; Dominguez, 1990; Soby, 1997). Its wood is soft and condensed, and its bark is usually gray, smooth and without fissures. Its branches and trunk are thick, and its roots are abundant, fibrous (Dominguez, 1990) and usually shallow. Fig leaves are palmate (Morton, 2000), large, petiolate and with three to seven lobes (Ferguson *et al.*, 1990). The leaves are a distinctive trait among fig varieties (Soby, 1997). *F. carica* is a gynodioecious species (Lisci and Pacini, 1994), i.e., the same species has specimens with male and female flowers, and others containing female flowers. Fig trees are usually grown in regions with mild winters and hot dry summers. Good conditions for fig growth are low relative humidity (lower than 25%), intense solar radiation, high summer temperatures (around 32–37 °C) and moderate winters (with temperatures above −1 °C) (Soby, 1997).

7.1.2 Worldwide importance and economic value

Figs are harvested worldwide on 459 754 hectares, with a production of over one million tonnes in 2007. Fig trees are widely planted in gardens throughout the Mediterranean region (and similar climates), and are well adapted to drought and high temperatures. Turkey and Egypt are the countries with highest fig production, representing approximately 50% of the world's production, followed by Iran, Algeria, and Morocco. The fig production of these top five countries accounts for 64% of the world's total. Turkey is also the number one country in fig exports, followed by the United States, Spain, Syria and Greece. The main fig importing countries are Germany, France, Italy and the United States (Food and Agriculture Organization [FAO], 2007). The United States imports of dried whole figs come mainly from Turkey, Greece and Mexico, whereas its imports of fig paste come mainly from Spain, Portugal and Turkey (California Fig Advisory Board [CFAB], 2006). Canada, Japan and Hong Kong are the three main markets for US dried fig exports (United States Department of Agriculture [USDA], 2004).

The United States ranks number six in fig production, with 4.6% of the world's total. In 2007, the United States produced 43 363 metric tonnes in 3680 hectares, with yields three times the global average (FAO, 2007). Figs are commercially produced in 14 US states; however, fig production is mainly concentrated in California (98%) (Stover *et al.*, 2007b).

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7.1.3 Culinary uses, nutritional value and health benefits

Figs are nutritious fruits rich in fiber, potassium, calcium and iron (CFAB, 2007; California Fresh Fig Growers Association [CFFGA], 2000; Chessa, 1997), with higher levels than other common fruits, such as bananas, grapes, oranges, strawberries and apples (CFFGA, 2000; Chessa, 1997; Michailides, 2003). Figs are sodium-free, fat-free and, like other fruits, cholesterol-free. Additionally, figs are an important source of vitamins, amino acids and antioxidants (CFAB, 2007; CFFGA, 2000; Solomon *et al.*, 2006). Compounds with antioxidant properties, such as vitamin C, tocopherols, carotenoids and phenolics, have been shown to be able to 'modify the metabolic activation and detoxification/disposition of carcinogens,' to affect processes that alter the development of tumor cells (Kader, 2001), and to avoid neurochemical and behavioral changes related to aging (Shukitt-Hale *et al.*, 2007). In addition, fruits and vegetables rich in phenolics have been shown to decrease cardio- and cerebrovascular diseases and cancer death rates (Hertog *et al.*, 1997). Dried figs are rich in polyphenols, such as anthocyanins and flavonoids, containing higher concentrations than most of the fruit and beverages consumed. Fig varieties with dark skin contain higher levels of polyphenols, anthocyanins and flavonoids, accompanied by a higher antioxidant activity, compared to fig varieties with lighter skin. Most of the compounds with antioxidant activity, such as anthocyanins and flavonoids, are located in the fig skin. Cyanidin (claimed to be the only anthocyanin in figs) is the main compound in skin pigmentation (Solomon *et al.*, 2006).

Figs are a very nutritious fruit that can be consumed either fresh or dried. Depending on the variety, dried figs can be commercialized for different uses, such as for table consumption or for processing as paste or canned (Aksoy, 1998). For instance, the variety 'Mission' can be used for dried fruit, paste or juice of concentrate, whereas the cultivars 'Kadota' and 'Adriatic' are mainly used for paste (Soby, 1997). In California, most of the fig production is used for the dried fig market (Soby, 1997; Tous and Ferguson, 1996), and mainly sold to cookie and energy bar companies (USDA, 2004). A large number of fig consumers use figs as an ingredient in baked goods and pastries, as a snack and in cooked dishes (Synovate, 2004). Dried figs can also be sold commercially as jam. Dried figs of low quality are used as ingredients for coffee and for juice concentrate. Moreover, fig culls and leaves can be used as animal feed (Aksoy, 1998).

Historical works provide evidence of the sustained importance and appreciation of figs in the Mediterranean area. Fig fruits, leaves and its latex have been used for traditional medicine. Pliny the Elder in his *Natural History* extolled 'one hundred and eleven observations' on the fig. Among them, 'This fruit invigorates the young, and improves the health of the aged and retards the formation of wrinkles.' The fig fruits have also been used against respiratory diseases (Guarrera, 2005). The fig leaves have been used against anemia and as an anthelmintic (Saeed, 2002). The fig latex (milky substance produced by the fig tree) has been used against warts and corns, as well as a remedy for insect bites (Guarrera, 2005).

In addition, figs have been used in industrial applications. Ficin, a proteolitic enzyme from the fig shoots and the immature fruits, can be used as a meat

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tenderizer, as a chillproofing agent in the beer industry, as a milk coagulant and for removing the casing of sausages (Aksoy, 1998).

7.2 Fruit development and postharvest physiology

7.2.1 Fruit morphology and types

The fig fruit is borne from a complex inflorescence called a syconium, which encloses hundreds of fruits. What commonly is called fig fruit is actually a developed syconium, considered a 'false fruit' (Lisci and Pacini, 1994). The true fruits are drupelets derived from flowers inside the syconium (Morton, 2000). The tiny flowers and even the initial prosyconium are so small that figs were once considered to bear fruit without ever forming flowers (reviewed in Condit, 1947). The syconium is connected to the exterior through a small aperture of little scales termed the ostiole or eye (Morton, 2000).

Figs are divided into four groups depending on their sex and pollination. These four groups are Caprifig (*F. carica* var. sylvestris Shinn.), Common fig (*F. carica* var. hortensis Shinn.), Smyrna (*F. carica* var. smyrnica Shinn.) and San Pedro (*F. carica* var. intermedia Shinn.). Common fig, Smyrna and San Pedro are the only edible types. They contain only long-styled female flowers, which produce more succulent fruitlets, and function as females. The Caprifig type contains staminate and short-styled female flowers and acts as male to pollinate the female figs (Hong and Chen, 2003). Some so-called Caprifigs are reported to be edible, and have a more succulent fruitlet than typical Caprifigs (Storey, 1975). The common type has completely parthenocarpic flowers (i.e., produce fruit without fertilization), Smyrna type has completely non-parthenocarpic flowers (i.e., need pollination to produce fruit) and San Pedro type needs pollination for the main crop, while the breba crop is parthenocarpic (Hong and Chen, 2003; Stover *et al.*, 2007b). Botanists use the term 'persistent' rather than parthenocarpic when referring to the fig, since it is not a true fruit. Common fig and San Pedro types usually have two crops a year. On the other hand, Smyrna types usually have one crop, and Caprifig types bear three crops a year (Ferguson *et al.*, 1990). As the name 'common fig' suggests, a high proportion of fig cultivars (78% of those listed by Condit) are 'common' (Kjellberg *et al.*, 1987). In California, the main Common fig cultivars are 'Kadota', 'Mission', 'Adriatic', 'Conadria', and 'Brown Turkey', the main Smyrna cultivar is Calimyrna, the only two commercial Caprifig cultivars are 'Roeding 3' and 'Stanford', and San Pedro fig types are not commercially important (Ferguson *et al.*, 1990).

Fig pollination, which is called caprification, is carried out by the fig wasp (*Blastophaga psenes* L.) (Hong and Chen, 2003; Stover *et al.*, 2007b) (see Fig. 7.1) which has coevolved with the fig (Kjellberg *et al.*, 1987). *B. psenes* completes its life cycle in the interior of Caprifig figs (Stover *et al.*, 2007b). After mating, female wasps go out of the Caprifig carrying along some pollen from the male flowers which are located next to the ostiole. When they enter the edible fig syconium they pollinate the long-styled female flowers although they cannot lay

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Fig. 7.1 Caprification (fig pollination) is carried out by the fig wasp (*Blastophaga psenes* L.). *B. psenes* completes its life cycle in the interior of Caprifig figs (male fig). When the female flowers are receptive for caprification, they secrete volatile compounds to attract the fig wasp, which will exit the male fig through the ostiole, transporting the pollen to the female figs.

eggs due to the flower anatomy. For commercial production, the Caprifig trees are grown separately from the Smyrna or San Pedro types in order to control caprification (only one wasp per fig) and avoid diseases. Therefore, caprification is achieved by manually locating cut Caprifig fruits in bags or baskets near the female flowers (Stover *et al.*, 2007b).

7.2.2 Fruit growth, development and maturation

Fig syconium growth (see Plate XII in the colour section between pages 274 and 275) occurs in three different stages, described by a double sigmoid curve. The first stage (period I), during the first six weeks of growth, is characterized by rapid diameter increase and slightly lower increases in moisture, fresh and dry weight, and sugar content. The second growth stage (period II), during the successive four weeks, is characterized by a reduction in diameter growth, moisture content, and fresh and dry weight accumulation rates. During this stage, sugar content is relatively unaltered. The third stage of growth (period III), during the remaining four weeks prior to maturation, is characterized by a marked increase in diameter growth, rates of fresh and dry weight, and both moisture and sugar content. During this final growth stage the fruit accumulates the majority of its sugar content, representing more than 90% of the sugar content of the mature fruit. Subsequently,

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more than 70% of its dry weight is accumulated during period III. The fig drupelets also experience this three-stage growth trend (Chessa, 1997; Crane and Brown, 1950; Ferguson *et al.*, 1990). Also at the beginning of phase III, the main epicuticular wax accumulation takes place in the form of regularly layered platelets. As ripening and senescence proceeds, wax quantity decreases and platelet structure changes, always maintaining a regular pattern (Chessa *et al.*, 1992).

7.2.3 Respiration and ethylene production

Fresh figs produce very low amounts of ethylene and carbon dioxide as indicated in Table 7.1.

7.2.4 Responses to ethylene

Figs are climacteric fruits and have their climacteric peak at the beginning of the third stage of growth (period III). Preharvest ethylene applications to figs have different effects depending on the stage of fruit development (Crane *et al.*, 1970b; Marei and Crane, 1971). Ethylene applied in period I inhibits fruit growth and triggers fruit abscission. Ethylene applied in period II stimulates fruit growth, and eventually abscission. In addition, this application also stimulates external color change while fruits do not undergo a complete maturation, lacking sweetness and flavor, and with mealy texture. Ethylene applied late in period II or in period III stimulates growth and maturity (Crane *et al.*, 1970a, 1970b). Ethylene has been used to regulate maturity uniformity since ancient times. Applications of olive oil on the ostiole ten days after the drupelets have turned red (Chessa, 1997) would ensure the presence of ethylene produced by degradation of the oil (Marei and Crane, 1971). Postharvest ethylene applications (continuous addition of 10 ppm) on ‘Brown Turkey’, ‘Kadota’ and ‘Sierra’ fig cultivars did not have an effect on fruit quality when stored at 0, 5 or 20 °C. Ethylene exposure only had an effect on the percentage of purple skin color of immature ‘Brown Turkey’ figs stored at 20 °C, inducing an increase of purple skin color from 8.3% to 100% in seven days (Crisosto *et al.*, 2007a).

Table 7.1 Fig respiration and ethylene production rates at different temperatures. To calculate heat production, multiply ml CO_2 $kg^{-1}\bullet hr^{-1}$ by 440 to get BTU ton-1 day-1 or by 122 to get kcal metric ton-1 day-1

Temperature (°C)	Respiration (ml CO_2 kg^{-1} hr^{-1})	Ethylene production (μl C2H4 kg^{-1} hr^{-1})
0	2–4	0.4–0.8
5	5–8	0.8–1.5
10	9–12	1.5–3.0
20	20–30	4.0–6.0

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7.3 Maturity and quality components and indices

Fig shape is usually obovoid, turbinate or pear-shaped. Its size may range from 2.5 to 10 cm in length. Fig color varies depending on the variety; some of the typical colors are yellow, green-yellow, copper color, red and purple. The skin is tender and thin, and the wall of the syconium is fleshy and either pale yellow, amber, light pink, red or purple (Morton, 2000).

Maturity stage at harvest has been shown to have an effect on fig soluble solids concentration (SSC), titratable acidity (TA), consumer acceptance, firmness and loss of firmness during storage, ethylene production, respiration rate, shelf life, ostiole diameter and shriveling (Bremer, 2008, Crisosto *et al.*, 2010). In addition, the level of latex on the fig decreases as fresh figs ripen, increasing consumer acceptance. Maturity stage also has an effect on flavor, for instance with undesirable flavors of overripe figs, due to fermentative products. On the other hand, fig weight, size, antioxidant capacity, skin color and thickness, split ostiole and blemishes were not affected by maturity stage (Bremer, 2008).

Fig firmness has been show to have a direct effect on the percentage of sound fruit, while the percentage of fruit with juice in the ostiole had a direct effect on the percentage of decayed fruit. The degree of liking by consumers and percentage of consumer acceptance has proved to be directly related to SSC and SSC:TA ratio, which become two important parameters when selecting for fresh fig varieties (Bremer, 2008). Other quality indices include absence of defects (such as bird-peck, sunburn, scab, skin break and stem shrivel), insects and decay. Cultivar selection, fruit maturity and postharvest technology during marketing should be evaluated to protect flavor and increase consumer consumption.

A consumer test evaluation on four fresh fig cultivars at two fruit maturity stages determined that the degree of liking was affected by cultivar and maturity stage at harvest, but there was no significant interaction between cultivar and maturity stage (Crisosto *et al.*, 2010). Figs harvested at tree ripe maturity had a significantly higher acceptance than figs harvested at commercial maturity. The average of all tested cultivars for the tree ripe figs reached 86% consumer acceptance while commercial mature figs had only 55% acceptance (Bremer, 2008). As a large number of consumers are still unaware of fresh figs, educational promotion should be pursued due to the large potential for the fresh fig market.

7.4 Preharvest factors affecting fruit quality

7.4.1 Breba

The first crop of the season is called the breba crop and the second crop is called the fig crop (see Fig. 7.2). In most cultivars, the fig crop is the commercial crop, while breba crop yields are very small to nearly non-existent (Dominguez, 1990) with less flavorful and lower quality fruit (Doster and Michailides, 2007). The fig industry has faced increased production costs during the last decade (Hendricks *et al.*, 1994) and as a consequence, harvest of the breba figs is cost prohibitive

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Fig. 7.2 Fig trees have two crops per year. The first crop of the season, called the breba crop, is produced from overwintering fruit buds in one-year-old shoots from the previous season. The second crop, called the fig crop, is produced from fruit buds that differentiate in the current season shoots. In the figure, the fruit furthest to the left on the shoot (set on wood from the previous year) is the breba crop and the fruit to its right (set on wood from the current season) is the fig crop.

(Crisosto *et al.*, 2010). If breba fruit are not harvested, they will persist on the tree or abscise, and eventually decay. These decayed breba are potential sites for fungal pathogens and may serve as insect attractants. In addition, spores produced on infected breba fruits can infect the commercial crop (Doster and Michailides, 2007). On the other hand, being the first crop, breba may be a very profitable option, and may represent the main crop. The Italian 'Petrelli' variety, with a very large, green, pear-shaped breba fruit ripening in the first week of June, is the earliest fig variety in the Mediterranean region, and brings a higher price on the fresh market, compared to all other varieties (Ferrara, 1990).

7.4.2 Fruit splitting

Fruit splitting is due to sudden changes in the internal pressure of the fruit. These changes in internal pressure can be the result of cool temperatures and high humidity while the fruit is maturing, precipitation at fruit maturity or over-caprification (excessive pollination). Splitting takes place in the ostiole. When figs split, the internal cavity of the syconium gets more exposed to the exterior; therefore, being more easily attacked by fungi and insects.

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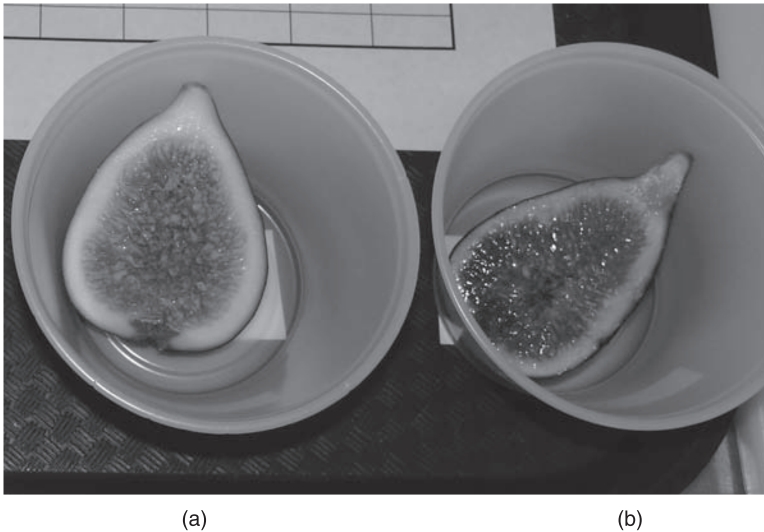
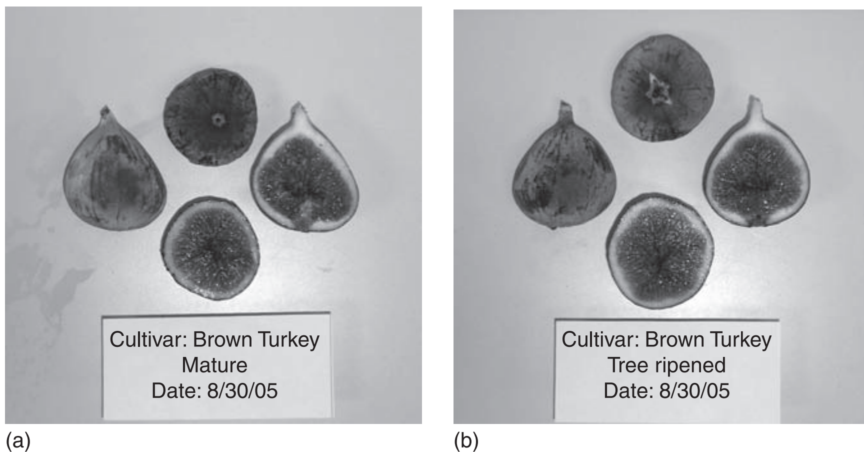
7.4.3 Maturity

Maturity stage at harvest has a clear effect on fruit quality attributes (Fig. 7.3, Fig. 7.4, Fig. 7.5, Fig. 7.6, Fig. 7.7, Fig. 7.8). In a study with ten different fig varieties, figs harvested at tree ripe maturity had higher SSC and SSC:TA ratio,



(a) (b)

Fig. 7.3 Fig internal differences at different stages of maturity: (a) commercial maturity and (b) tree ripe maturity. A fig fruit is considered commercially mature when the fruit is harvested physiologically mature, but not ripe, and when the flesh gives a little to the touch, while a fig fruit is considered tree ripe mature when the fruit is harvested ripe and softer than commercial maturity, but not overripe.



(a) (b)

Fig. 7.4 'Brown Turkey' fig (externally and internally) harvested at two different maturity stages: (a) commercial maturity and (b) tree ripe maturity.

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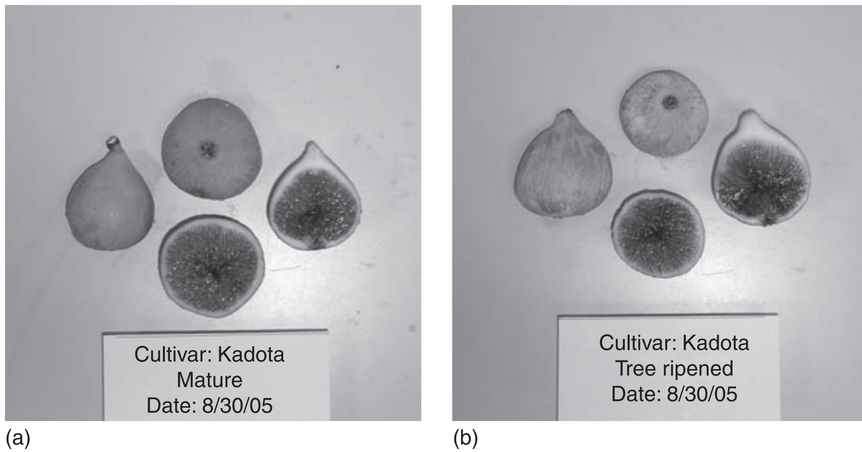

Fig. 7.5 'Kadota' fig (externally and internally) harvested at two different maturity stages: (a) commercial maturity and (b) tree ripe maturity.

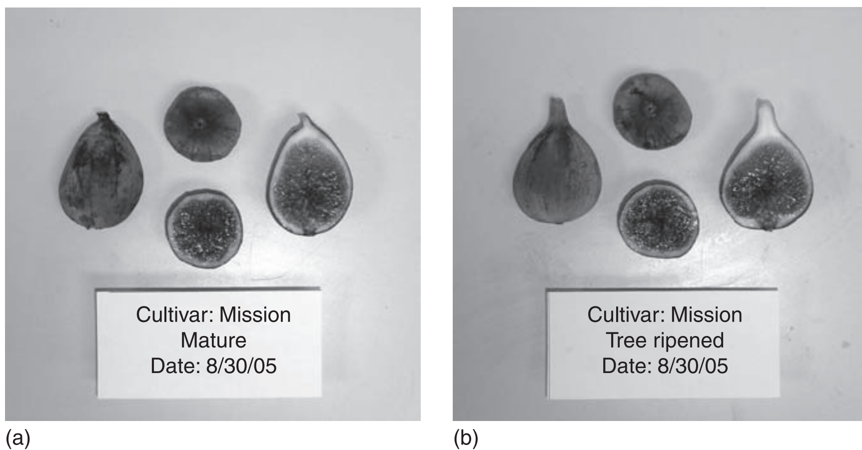

Fig. 7.6 'Mission' fig (externally and internally) harvested at two different maturity stages: (a) commercial maturity and (b) tree ripe maturity.

lower TA, higher consumer acceptance and lower initial firmness than figs harvested at commercial maturity. Tree ripe figs typically had lower ethylene production and respiration rates than figs harvested at commercial maturity. This decrease in ethylene production from commercial maturity to tree ripe maturity may be explained by the fact that the fig climacteric peak occurs prior to commercial maturity (Chessa, 1997; Crisosto's personal communication). Figs harvested at commercial maturity had longer shelf life than those harvested at tree ripe maturity, remaining sound and free of decay and off-colors for a longer time after a week of cold storage (shelf life). Tree ripe figs had also larger ostiole

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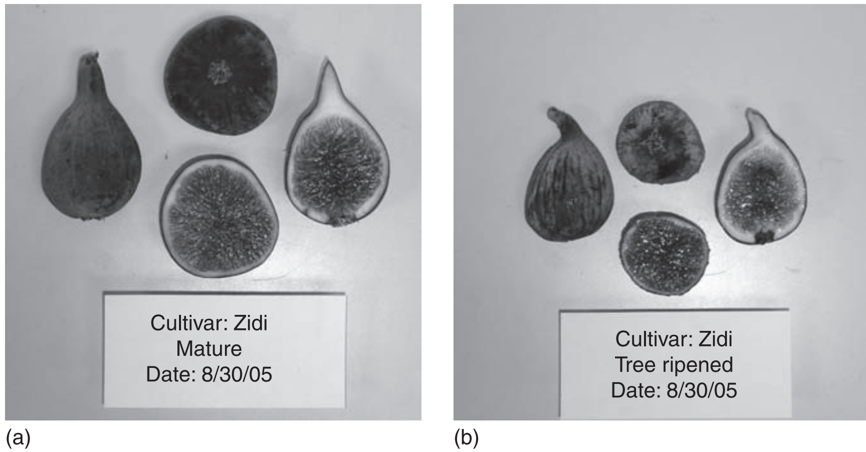

Fig. 7.7 'Zidi' fig (externally and internally) harvested at two different maturity stages: (a) commercial maturity and (b) tree ripe maturity.

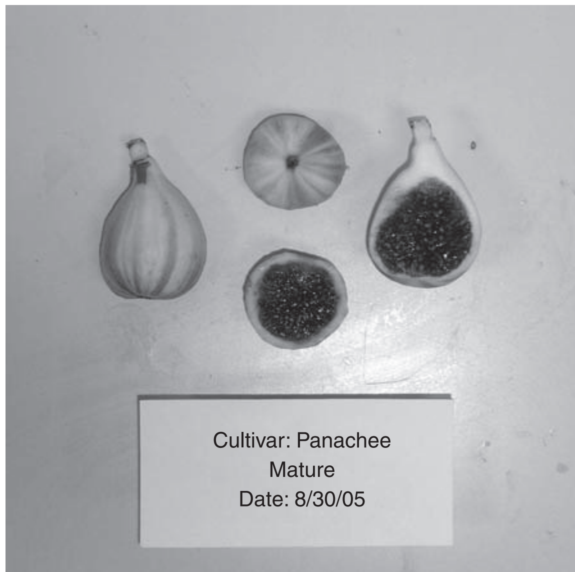

Fig. 7.8 'Panachee' fig (externally and internally) harvested at commercial maturity.

diameters and were more affected by shriveling than figs harvested at commercial maturity. Maturity stage at harvest did not have an effect on fig weight, size, antioxidant capacity, skin color and thickness, split ostiole and blemishes (Bremer, 2008).

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7.4.4 Genotype

Fruit weight and size (diameter and length), SSC, TA, and SSC:TA ratio, skin color (luminosity, chroma and hue), ethylene production and respiration rates (CO_2 production), firmness, ostiole diameter, internal cavity diameter, shriveling, growth cracks, shelf life and susceptibility to blemishes are affected by genotype. In a study of ten fig varieties (152–4s, 'Brown Turkey', 'Kadota', 'Mission', 'Orphan', 'Panachee', UCR 276–14, UCR 291, 'White Texas Everbearing' and 'Zidi') grown under California conditions, fig weight (20–60 g) was comparable to that of Turkish varieties (22–52 g (Çalişkan and Polat, 2008), 40–65 g (Bostan *et al.*, 1998), and 30–90 g (Özeker and Isfendiyaroglu, 1998)). The varieties grown in California had similar fruit length (41–63.5 mm) to varieties from Turkey (38.5–62.0 mm), but were smaller in fruit diameter (35.6–48.4 mm versus 45.0–55.0 mm) (Bostan *et al.*, 1998). Soluble solids concentrations of these varieties grown in California (13%–31%), though with more extreme values, were in general comparable to the Turkish varieties (15.1%–21% (Bostan *et al.*, 1998), 16%–27% (Özeker and Isfendiyaroglu, 1998), and 20.1%–27.4% (Çalişkan and Polat, 2008)). Finally, TA of the varieties grown in California (0.14%–1% citric acid) was in general higher than the varieties from Turkey (0.09%–0.26% (Çalişkan and Polat, 2008), 0.14%–0.22% (Bostan *et al.*, 1998), and 0.06%–0.15% (Özeker and Isfendiyaroglu, 1998)).

Green varieties (such as 152–4s, 'Kadota', 'Orphan', 'Panachee', UCR 276–14, UCR 291, and 'White Texas Everbearing') have higher luminosity and chroma than dark varieties (such as 'Brown Turkey', 'Mission', and 'Zidi'), which indicates lighter and more intense skin color. Green varieties' hue value usually ranges around the green-yellow colors (around 106°), while dark varieties' value may range around purple colors (314°) or reddish colors (13°).

Firmness from the ten fig varieties grown under California conditions ranged from 7.6–20 N when harvested at commercial maturity and from 6.2–10.2 N when harvested at tree ripe maturity. Ethylene production ranged from 3.5 to 17 $\mu L\ C_2H_4 \cdot kg^{-1} \cdot hr^{-1}$ and the respiration rate ranged from 34.8 to 79.6 mL $CO_2 \cdot kg^{-1} \cdot hr^{-1}$ (Bremer, 2008).

7.4.5 Cultural practices

Fig tree pruning, training, health, nutrition and irrigation also have an effect on fruit quality (Condit, 1947).

7.5 Postharvest handling factors affecting quality

7.5.1 Temperature management

Postharvest temperatures are critical for fresh figs. For instance, in California, 'Black Mission' and 'Calimyrna' figs stored in optimum conditions (−1 to 0 °C) have an expected postharvest life of 1–2 weeks in air, and 3–4 weeks in a controlled atmosphere (Chessa, 1997; Crisosto and Kader, 2007). 'Mission' figs stored at

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5 °C almost doubled their respiration rate compared to fruits stored at 0 °C, while their ethylene production was almost 50 fold (Colelli *et al.*, 1991). Similar results were reported for 'Calimyrna' (Colelli and Kader, 1994). Fresh fig shelf life (i.e., the period in which the fruit maintains its commercial quality at room temperature (Iungerman, 2005)) is extremely short, lasting 1–2 d at 20 °C after storage at 4–6 °C and 75% relative humidity (Morton, 2000).

7.5.2 Physical damage

Fresh figs are very perishable (Alayunt *et al.*, 1998; Çelikel and Karaçalı, 1998; Piga *et al.*, 1998; Stover *et al.*, 2007b), sensitive to physical damage and highly susceptible to postharvest decay infections (Chessa, 1997; Piga *et al.*, 1998; Venditti *et al.*, 2005). Fresh fig quality (taste and aroma) increases with ripening; however, its sensitivity to damage also increases, resulting in reduction of its market life (Stover *et al.*, 2007b; Chessa, 1997). Figs have a very short storage and shelf life. This is mainly due to their fast ripening (Çelikel and Karaçalı, 1998; Venditti *et al.*, 2005) and high susceptibility to decay (Venditti *et al.*, 2005), which is the result of their easily damaged epidermis and high sugar content (Kaynak *et al.*, 1998). The fruit epidermis is very sensitive to pressure and knocks (see Plate XIII), which can cause fig bruising, splitting and injuries, favoring pathogen infections (Chessa, 1997). Sensitivity to physical damage is affected both by fig cultivar and by maturity stage at harvest (Bremer, 2008).

7.5.3 Water loss

Fig water loss can be reduced with early cold storage (see Fig. 7.9). 'Brown Turkey' figs exposed to six hours of delayed cooling (at ambient temperature) resulted in an initial weight loss of around 5.9% weight, in comparison to 4.8%

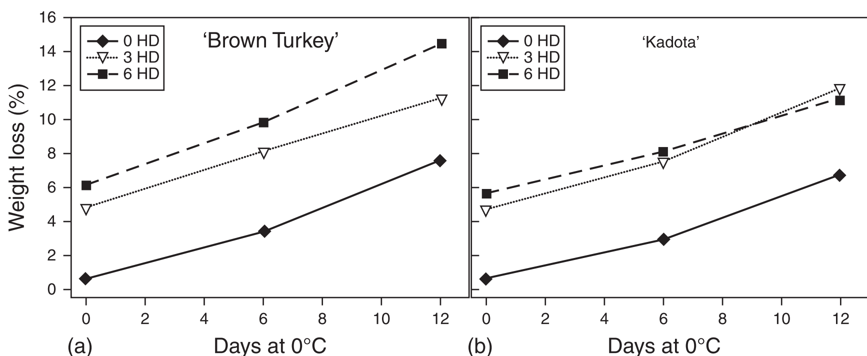

Fig. 7.9 Effect of delayed cooling on weight loss of (a) 'Brown Turkey' fig and (b) 'Kadota' fig. Treatments: 0 HD = no delayed cooling, stored immediately at 0 °C; 3 HD = 3 hours in the sun before storage at 0 °C; and 6 HD = 6 hours in the sun before storage at 0 °C.

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weight loss for three hours of delayed cooling, and 0.6% weight loss for 0 hours of delayed cooling. 'Kadota' figs also had higher weight loss when exposed to delayed cooling compared to immediate cooling. Weight loss during cold storage at 0 °C increased proportionately, according to previous losses, for the three delayed cooling treatments. In addition, firmness was also affected by delayed cooling, decreasing firmness with increased delayed cooling period. In general, shorter periods of delayed cooling tended to produce a higher percentage of quality fruit during storage life and shelf life (Dollahite *et al.*, 2007).

7.5.4 Atmosphere

Storage in a controlled atmosphere (CA) with 5%–10% oxygen and 15%–20% carbon dioxide is beneficial to reduce decay, maintain firmness and reduce respiration and ethylene production rates. Reduction of respiration and ethylene production rates will lengthen fresh fruit life (Chessa, 1997; Crisosto and Kader, 2007). Extended storage in CA can result in loss of characteristic flavor. Good quality of fresh 'Mission' figs was maintained for up to 4 weeks when kept at 0, 2.2, or 5 °C in atmospheres enriched with 15% or 20% CO_2. The visible benefits of exposure to high CO_2 levels were reduction of decay incidence and maintenance of bright external appearance. Ethylene production was lower, and fruit softening (as measured with a deformation tester) was slower in the high-CO_2-stored figs than in those kept in air (Colelli *et al.*, 1991). Similar results were observed for 'Calimyrna' figs (Colelli and Kader, 1994). On the other hand acetaldehyde concentration of the CO_2-treated 'Mission' fig fruit increased during the first week, then decreased while ethanol content increased slightly during the first three weeks and moderately during the fourth week and this may potentially result in off-flavor (Colelli *et al.*, 1991).

Exogenous ethylene exposure during cold storage has been shown to have no effect on fruit quality. For instance, continuous ethylene addition of 10 ppm on 'Brown Turkey', 'Kadota' and 'Sierra' fig cultivars did not affect fruit quality (such as fig firmness, internal maturity, percent of sound fruit (commercial fruit), percent of fruit with decay, and percent of fruit with off-color) when stored at 0, 5 or 20 °C (Crisosto *et al.*, 2007a).

7.6 Physiological disorders

7.6.1 Chilling injury or other physiological disorders

Chilling injury or other physiological disorders have not been observed or reported.

7.7 Pathological disorders

Fig diseases cause important repercussions in fig production. The diseases causing the most damage in California are endosepsis, smut, and souring (or fermentation).

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The combination of these three diseases is responsible for losses of up to 50% of the total production (Michailides, 2003).

Endosepsis disease is caused by *Fusarium* spp, especially *F. lactis*, and mainly transported by infected fig wasps. Therefore, cultivars that need caprification are more likely to be affected. Endosepsis affects fig flowers. Endosepsis appears in the cavity of the fig, making the pulp soft, watery and brown with sometimes an offensive odor. Good practices to control this disease are separation of Caprifigs from female figs, good field sanitation and treatments applied to Caprifig crops.

Smut is caused by *Aspergillus nigri* vars. In reality, it is not a smut; however, it is called a smut because it resembles one. The fungus produces abundant black powdery conidia in the cavity of ripe fruits. The decay usually starts in the ostiole, and later it spreads around the ostiole as water-soaked areas. Good strategies to manage fig smut are the removal of old fruit culls and refuse, as well as reducing fruit contamination with dust.

Souring or fermentation spoilage of the figs takes place when the fruit is still on the tree. The agents that cause souring are yeasts and bacteria, which are transported by insects. Souring symptoms are only noticeable when fruits are ripe and have the ostiole wide open. Ostiole aperture is necessary for the presence of this disease, since the ostiole is the way of entrance for the vector insects. Therefore to control this disease it is necessary to eradicate the vector insects.

Other fig diseases present in California are armillaria root rot (*Armillaria mellea*), aspergillus mold (*Aspergillus* spp.), bacterial canker (*Psedomonas fici*), botrytis limb blight and fruit rot (*Botrytis cinerea*), fig mosaic (not characterized or isolated yet), phytophthora fruit rot (*Phytophthora palmivora*), soft rot (*Rhizopus stolonifer*) and surface mold or contact spot (*Alternaria alternate, Aspergillus niger*, and *Cladosporium herbarum*) (Fig. 7.10).

Figs are very susceptible to decay, which significantly reduces their cold storage and shelf life. Decay reduction on fresh figs is a difficult task (Venditti *et al.*, 2005), due in part to the lack of registered postharvest products. To reduce postharvest diseases, the first step is an effective preharvest control of diseases

(a)

(b)

Fig. 7.10 Fresh figs are very susceptible to decay, which significantly reduces their cold storage and shelf life. Pictured: (a) *Alternaria alternate* and (b) *Cladosporium cladosporioides*.

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and insects. Preharvest diseases will continue to develop after harvest. Insects can damage the fruit, increasing fruit susceptibility to decay, or act as a fungus vector (Crisosto *et al.*, 2006). Cultivar selection can also be a strategy for reducing pathogen attacks. For instance, varieties with smaller ostioles (i.e., the apical orifice) are less affected by decay (Doster *et al.*, 2002).

Sulfur dioxide (SO_2) fumigations are currently used commercially on grapes. These fumigations have been shown to prevent fungi growth and delay disease development when fruits are exposed to air (Sholberg, 2004). 'Brown Turkey' and 'Kadota' fig exposed to 25 part per million per hour (ppm-hr) previous to cold storage increased the percentage of sound fruit during shelf life (Crisosto *et al.*, 2007b). The use of SO_2 generating pads, the combination of pads and sulfur dioxide fumigations, and the use of repeated fumigations during the cold storage have also been shown to reduce the percentage of decay during the shelf life of fresh figs. The use of SO_2 technology has shown a noticeable reduction in the number of colonies of pathogens growing on the surface of figs. Most of the investigated pathogens (*Alternaria* spp., *Aspergillus flavus, Bacillus* spp. (RGP5 and RPG3), *Botrytis cinerea, Penicillium* spp., and *Rhizopus stolonifer*) had low rates of survival when exposed to SO_2 fumigation at 100 ppm on media at 20 °C. Sulfur dioxide fumigation at 0 °C was less effective than at 20 °C, with higher levels of pathogen survival (Cantin's personal communication). Consequently, the use of sulfur dioxide can be a potential tool for the control of postharvest rotting of figs.

Treatments with hot water dips have been shown to reduce decay in several fruit commodities. A study on the fig variety 'Niedda Longa' showed that one-minute dips in hot water at 60 °C with 0.5% sodium carbonate significantly reduced decay. After the dip, figs showed 0% decay and 14% decay after 1 and 2 weeks respectively, stored at 5 °C and 90% relative humidity. The percentage of decay for the control was 26% and 50% after 1 and 2 weeks respectively. In addition, the figs dipped in hot water at 60 °C with 0.5% sodium carbonate had the best visual appearance up to 2 weeks. The treatment did not affect fig weight loss (Molinu *et al.*, 2006).

Treatments with sodium carbonate and acetic acid have shown efficient control against *B. cinerea*. In another study, two fig varieties, a black ('Craxiou de Porcu') and a white ('Rampelina') were treated with either a solution of 1% sodium carbonate or vapors of 100 ppm acetic acid. Both treatments significantly reduced diseases after 2 weeks of storage at 2 or 8 °C and 90% relative humidity. Neither treatment showed damages. Fruit weight, pH, acidity and total soluble solids were not affected by the treatments (Venditti *et al.*, 2005).

Decay reductions have also been shown with fruit exposure to a nitrogen atmosphere. In a different study, the fig variety 'Niedda Longa' was exposed for 12 hours to a 99% nitrogen plus 1% oxygen atmosphere. This treatment significantly reduced decay, from 27% decay for the control to 12% after 3 days. In addition, the treatment presented fruits with better overall appearance and without negative effects in taste (Piga *et al.*, 1998).

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7.8 Insect pests and their control

Fig trees are highly susceptible to nematodes, especially in sandy soils. Root-knot nematodes may be the most widespread fig parasite. These nematodes cause knots or galls on the fig roots. Nematode effects can be reduced with fumigation; however, this practice may be expensive in fig orchards (Michailides, 2003). Aphids, birds, fruit flies, and scale insects may cause occasional damage (Tous and Ferguson, 1996).

7.9 Postharvest handling practices

7.9.1 Harvest operations

Brebas are the first figs of the season, setting on wood from the previous year, and typically mature in June in the central valley of California. The main crop (fig crop) is produced on the current season's wood, maturing fruit in the central valley from August to September (Obenauf *et al.*, 1978) or even later in a warm year.

Dried figs are mechanically swept from the ground and washed. They are harvested during September–October (Tous and Ferguson, 1996), with harvests every 2–3 weeks (Soby, 1997). Fresh figs are harvested manually based on firmness and color change (Tous and Ferguson, 1996). Figs at harvest should give a little to the touch but still be firm. Dark-skinned varieties should be harvested before turning completely dark, while green-skinned varieties should be harvested when they appear yellowish-white to light yellow. Fresh figs' skin color and flesh firmness are related to their quality and postharvest life.

Achievement of ripeness of the fig crop is sequential; the first fig fruits to ripen are those at the base of the new shoots, and they ripen consecutively towards the distal end of the shoot. In the case of fresh fig production, this sequential ripeness makes multiple harvest dates necessary in order to harvest the fruit at its optimal time. Fresh figs are usually harvested daily or weekly for 4–6 weeks (Tous and Ferguson, 1996). By contrast, the breba crop achieves ripeness over a more concentrated period of time (Stover *et al.*, 2007b).

Fresh fig harvesting must be done carefully, minimizing physical damages, abrasions, and cracks that will make the fruit more susceptible to decay (Crisosto *et al.*, 2006). In order to avoid fruit damage, figs should be harvested early in the morning, detaching the fruit with a clean cut and avoiding lesions (Chessa, 1997). The use of gloves while managing figs also helps reduce fruit damage and bruising, as well as protecting the skin from the latex (caustic milky exudate) released from the broken stem (Tous and Ferguson, 1996). Fresh figs must be exclusively harvested from the tree, never from the ground (see Fig. 7.11). In addition, containers used at harvest and at transportation require previous strict sanitation in order to reduce disease exposure (Fig. 7.12). After harvest, fresh fruit must be cooled down as soon as possible to 0 °C, and the cold chain must be maintained throughout its handling and until it reaches the consumer (Crisosto *et al.*, 2006).

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Fig. 7.11 Manual harvesting of 'Brown Turkey' figs for fresh consumption. Trees for fresh fig production are usually trained low for ease of harvesting. Fresh fig harvesting must be done carefully, minimizing physical damage, abrasions, and cracks.

Fig. 7.12 Fresh figs are harvested into small containers to avoid damage and pressure among fruit. In these containers figs are transported from the field to the packing area (usually at the side of the field).

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Harvest efficiency depends on the fruit size, the percentage of fruit to harvest, the accessibility and the person harvesting (Chessa, 1997). Harvest is an important part of the production cost.

7.9.2 Packinghouse practices

After harvest, California fresh figs are usually packed at the side of the field, to avoid having the fruit under pressure for a long time. Packing takes place in sheds to avoid excessive heat that would reduce shelf life (see Fig. 7.13, Fig. 7.14). The fruits are packed in containers that allow air circulation (Chessa, 1997), usually on trays or clam shells (Fig. 7.15). The trays or clam shells are then put into boxes and stacked on pallets for transport. It is very important to maintain the cold chain during packing, storage and transportation in order to improve fig shelf life (Crisosto *et al.*, 2006).

7.9.3 Control of ripening and senescence

Figs have a very fast ripening, which accelerates fruit softening (Çelikel and Karaçalı, 1998; Venditti *et al.*, 2005), and consequently shortens fig shelf life. However, fresh fig ripening can be reduced with low temperatures (Venditti *et al.*, 2005) and controlled atmospheres (Crisosto and Kader, 2007). Controlled atmosphere with 5%–10% oxygen and 15%–20% carbon dioxide reduces decay, maintains firmness, and reduces respiration and ethylene production rates. An initial application of CO_2 at 5–10 °C reduces respiration rates and the development

Fig. 7.13 Packing area for fresh figs at the side of the field. Shading avoids excessive heating of the fruit that would reduce shelf life.

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Fig. 7.14 Packing figs at the side of field immediately after harvest. The use of gloves while managing figs helps reduce fruit damage and bruising, as well as protecting the packer's skin from the latex released from the broken stem.

(a)

(b)

Fig. 7.15 Different types of containers for packing fresh figs: (a) trays, (b) clam shells. Containers must allow air circulation.

of pathogens (Chelsea, 1997). Exogenous ethylene exposure (continuous addition of 10 ppm) can be used to induce skin color change in dark varieties, such as 'Brown Turkey' (Crisosto *et al.*, 2007a).

Modified atmospheres can be created with polyethylene films, either by packing the fruit individually, in trays or in small containers (Chessa, 1997).

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7.9.4 Recommended storage and shipping conditions

The optimal storage conditions for fresh figs are temperatures around –1 to 0 °C with a relative humidity of 90%–95%. Forced-air cooling to 0 °C is recommended (Chessa, 1997; Crisosto and Kader, 2007). However, the expected storage life of fresh figs is also dependent on the fig variety and its degree of ripeness (Chessa, 1997; Crisosto and Kader, 2007, Bremer, 2008). Controlled atmospheres, modified atmospheres and modified atmosphere packaging with reduced levels of oxygen and high levels of carbon dioxide (not more than 25%) have shown beneficial effects on fresh fig storage, prolonging their shelf life (Chessa, 1997; Crisosto and Kader, 2007).

7.10 Processing

7.10.1 Fresh-cut processing

Fresh-cut figs (maroon-skinned 'Brown Turkey' and yellow-green skinned 'Sierra') at commercial maturity prepared by sanitizing intact fruit in chlorinated water, cut (halved) with a sharp stainless steel knife and stored in clamshells remained in excellent condition for 6 days in air at 0 °C or 5 °C or in a controlled atmosphere (3% O_2 + 6, 12 or 18% CO_2) at 5 °C. After 9 and 12 days, storage at 0 °C resulted in the best quality cut figs, but figs were also of marketable quality when stored at 5 °C in atmospheres with 12% and 18% CO_2. However, the 12 and 18% CO_2 atmosphere resulted in notable increases in fermentative volatiles (ethanol and acetaldehyde). Visual quality of the cut figs was not affected by maturity stage. Loss of visual quality was associated with damage to the peel of the fruit and there was no discoloration of the cut surfaces in either cultivar. Sugar concentrations of the cut figs decreased significantly in 'Brown Turkey' fruit but not in the 'Sierra' fruit over 12 days. Respiration rates of intact and cut figs were similar (4–5 and 7–8 μL $CO_2 g^{-1}h^{-1}$ at 0 °C and 5 °C for 'Brown Turkey' figs, and 6–7 and 9–10 μL CO_2 $g^{-1}h^{-1}$ at 0 °C and 5 °C for 'Sierra' figs). Ethylene production rates were also similar in fruit at the two stages of maturity, but different between the cultivars. Microbial growth on the cut surfaces was similar to that of the intact fruits, due mostly to molds, and did not appear until after 12 days at 5 °C in air. The CO_2 atmospheres were effective in retarding microbial growth. Based on these results, it appears that figs could perform well as fresh-cut products and add interest and diversity to fruit trays held at very low temperatures for about 9 days.

7.10.2 Other processing practices

Figs grown for eating as dried fruit go through normal senescence in the orchard. Thus, figs ripen fully and dry partially on the tree; they then fall to the ground, where further drying occurs. Most figs are mechanically harvested from the ground, although some hand labor at harvest is still used. A typical operation involves mechanical sweeping of figs from under the trees into a windrow in the center of each row. Further drying may take place here before mechanical

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harvesters remove the fruit from the ground and place it in bins (approximately 1000 pounds of fruit). Leaves, small branches, small stones and other debris are separated from the figs during harvest. Harvest continues for 4 to 6 weeks at weekly intervals. After harvest, the fruit is transported to a collection site, dehydrator or storage area, where it is fumigated to eliminate insects. Figs for drying often require additional moisture removal following harvest. This can be done by sun drying or dehydration. Usually the fruit is subjected to a rapid water rinse before it is dried. With sun drying, the fruit is placed in single layers on wooden trays and spread in direct sun. Fruit to be dehydrated is also placed on trays, which are stacked and moved into dehydrating tunnels. The objective of drying is to reduce fruit moisture to about 17%. This may take a few days in the sun or 6 to 12 hours at 60 °C in dehydrators. Care should be taken to prevent tunnel temperatures from getting too high, since caramelization can occur. This results in a burnt flavor and dark-colored fruit. After drying, the fruit is again fumigated to control insects.

Canning figs are picked from trees as they become fully colored and while they are still firm. Harvest is by hand, often from ladders, and the figs are placed in buckets or shallow flats. Pickers wear gloves because latex exuded from freshly harvested fig stems causes skin irritations. Actual fruit removal from the branches is usually accomplished by grasping the fig in the hand while twisting and pulling in one motion. Fresh figs are highly perishable, so it is exceedingly important to transport the harvested product without delay to a cold storage facility.

Efforts are ongoing to develop possible new fig products through the combination of different technologies including reduction of water activity (aw) and high pressure processing (Carbone *et al.*, 2001). Very promising results related to physical, chemical and microbial attributes were obtained when fruits were dipped for 15 minutes in a 0.5% ascorbic acid solution, partially dehydrated in cold air (up to 0.87 of water activity), then packaged in fructose isotonic solution and processed at 600 MPa for 3 minutes. In these conditions fruits retained more fresh-like attributes and lower microbial population compared to other treatments (blanching, dehydration and modified atmosphere packaging) and kept those characteristics for 28 days at 5 °C.

7.11 Conclusions

As a complement to the rich pleasures of dried figs and their products, there is a great deal of interest in expanding fresh fig sales in the U.S. This will require significant advances in postharvest handling. The large number of consumers still unaware of figs, combined with positive consumer perception, points to the large potential for the fig market, especially the fresh fig market. It is necessary to develop cultivars better suited for fresh consumption that have better taste at the less mature stage and/or remain firm enough at the tree ripe stage to tolerate postharvest handling during harvesting and marketing. Different ways of packing and marketing to protect safety and quality of this fresh commodity should be investigated.

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7.12 References

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(a)

(b)

Plate XI (Chapter 6) Chilling injury in feijoa. (a) Internal symptoms include vascular browning and pink discoloration of the flesh; (b) external symptoms include longitudinal browning of the skin.

Plate XII (Chapter 7) Different stages of fig fruit development, externally and internally.

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Plate XIII (Chapter 7) Fresh figs are very sensitive to physical damage, one of the main reasons for their short shelf-life.

Plate XIV (Chapter 8) Miniature and large types of golden apple fruits.

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8

Golden apple (*Spondias dulcis* Forst. syn. *Spondias cytherea* Sonn.)

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Abstract: The golden apple (*Spondias dulcis* Forst. syn. or *Spondias cytherea* Sonn.) is native to Polynesia, and has been widely distributed to many tropical and sub-tropical regions of the world. This fruit is climacteric in nature and exists in two forms: the large type and the miniature or dwarf type. Fruits at the mature-green, semi-ripe and ripe stages of maturity are used in both fresh and processed forms and are a major export fruit and foreign exchange earner for many Caribbean islands. This chapter reviews golden apple development, postharvest physiology and nutritional value, pre- and postharvest factors affecting fruit quality, including pathological disorders and insect pests, processing technologies and applications.

Key words: golden apple, climacteric, respiration, chilling injury, heat injury, senescence.

8.1 Introduction

8.1.1 Origin, botany, morphology and structure

The golden apple (*Spondias cytherea* Sonnerat or *Spondias dulcis* Forst.) (also called otaheite apple, ambarella, Polynesian plum, caja-manga, jew plum, june plum, pomme cythere, kedongdong, ma-kok-farang, mokak, coc, juplón, hobo de racimos, jobo de la India, jobo de Indio, mango jobo and manzana de oro) belongs to the Anacardiaceae family which also includes several important tropical fruit trees such as mango (*Mangifera indica* L.) and cashew (*Anacardium occidentale* L.) Native to Polynesia, it was introduced into Jamaica in 1782 and again ten years later by Captain Bligh, and can now be found growing throughout the Caribbean, Asia, South and Central American regions and, to a lesser extent, in Africa (Morton, 1987). It is common in Malaysian gardens and fairly frequent in India and Ceylon.

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The United States Department of Agriculture in Washington received seeds from Liberia (West Africa) in 1909 and from Queensland (Australia) in 1911, where it can also be found. Although a number of collections were grown in Florida, from Palm Beach southward, the tree has never become common there.

The golden apple tree flourishes in humid tropical and subtropical areas and can grow at an altitude of up to 2300 ft (700 m). Of the two distinct types of golden apple fruits, the large type, which is more popular, is borne on trees attaining a height of 9–25 m, although Daulmerie (1994) reported trees of up to 45 m. The miniature or dwarf type is from trees about 1.5–3 m in height. The trees start to bear fruit after 2–3 years of growth when propagated by cuttings and yield increases to 8 years with an economic life of 20–25 years. Fruit from trees of both types are normally oval, round or pear-shaped. Fruit of the large type vary in size from about 5–6 cm in diameter and 9–10 cm in length with an average weight of 200g (Mohammed and Wickham, 1997). Fruit of the miniature or dwarf type are about 4–5 cm in diameter and 5–6 cm in length with an average weight of 65 g (Graham *et al.*, 2004b; Persad, 1996; Winsborrow, 1994). (See Plate XIV in the colour section between pages 274 and 275.) The trees of both types, which are stately ornamentals, are rapid-growing, upright and rather rigid and symmetrical, with thick, breakable branches. They have deciduous, pinnate leaves 20–60 cm in length, composed of 9–25 glossy, elliptic or obovate-oblong leaflets 6.25–10 cm long, finely toothed towards the apex (Morton, 1961).

The trees exhibit a short dormant period in the early dry season, their leaves turn light yellow and then senesce and abort. Flowering is subsequently initiated and fruits ripen in 6–7 months (Bauer *et al.*, 1993). The trees produce flowers 4 years after planting and continue to produce good yields after 25 years. The small, inconspicuous, whitish flowers are borne in large terminal panicles. They are assorted, male, female and perfect in each cluster. The fruit are long-stalked and are borne in clusters of a dozen or more. They have thin but tough skin, which is often russetted. While the fruit is still firm, the flesh is crisp, crunchy, juicy, slightly sour and has a somewhat pineapple-like fragrance and flavour (Morton, 1961; Mohammed and Wickham, 1997). If allowed to soften, the aroma and flavour become musky and the flesh difficult to slice because of conspicuous and tough fibres or spines extending from the rough ridges of the five-celled, woody core (Morton, 1961; Graham *et al.*, 2004b).

8.1.2 Worldwide importance and economic value

Previously the golden apple was generally not grown as a commercial crop and exporters were cautious about marketing such an obscure fruit (Bauer *et al.*, 1993). However, extra-regional export markets became established in the late 1980s and the large type fruit is now exported from several Caribbean countries including Trinidad and Tobago, Grenada, St Vincent, Guyana, Surinam, Jamaica, the Dominican Republic and Dominica as a fresh fruit while mature-green to North America and European countries. According to Bauer *et al.* (1993), Grenada was able to penetrate the lucrative fresh-fruit market of the United States in the

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1980s because of its fruit fly-free status. A number of value-added products made from golden apples such as amchar, chutney, pickles (sweet and sour), are also in demand in the ethnic markets in Canada, the United States and the United Kingdom.

However, the miniature or dwarf golden apple fruit remains unexploited although it has great potential for domestic utilization and foreign trade because of several advantages it has over the large fruit type. Among the main advantages are that the miniature fruit is available throughout the year while the large fruit type is seasonal in nature; fruits from the dwarf trees are less cumbersome to harvest due to the significant difference in tree height; early bearing is associated with the miniature or dwarf types as initial bearing occurs in six months compared to several years in the large type; the miniature plants can be established at very high densities giving high yields per unit area compared to the large type trees; the miniature fruit lends itself more easily to certain types of processing (Graham *et al.*, 2004b; Mohammed and Wickham, 1997).

8.1.3 Culinary uses, nutritional value and health benefits

Both types of golden apple fruits are mainly used as foods. They are very versatile since they are eaten raw at the mature-green stage and also as a dessert at the fully ripe stage. In Malaysia, golden apple is often cut into pieces and eaten with salt or a black shrimp paste called 'hayko'. The mature green fruits also produce a delicious juice, which is used in drinks and sherbets. Beyond the mature-green stage the fruits can be processed in numerous ways. For example the crisp sliced flesh can be used as a curry ingredient, or stewed with a little water and sugar and then strained through a wire sieve to make a product similar to apple sauce but with a richer flavour. With the addition of cinnamon or any other spices desired, this sauce can be cooked down to a thick consistency to make a preserve very similar to butter. Unripe fruits can be made into jelly, pickles or relishes, or used for flavouring sauces, soups and stews. Young golden apple leaves are appealingly acid and consumed raw in south-east Asia. In Indonesia, they are steamed and eaten as a vegetable with salted fish and rice, and also used as seasoning for various dishes. They are sometimes cooked with meat to tenderize it (Morton, 1961).

The ripe fruit is much sweeter (6% soluble solids concentration) than green fruit (4% soluble solids concentration). According to Morton (1961), the food value of golden apple fruits per 100 g of edible portion is 157.30 calories; total solids range from 14.53–40.35%, moisture 59.65–85.47%, protein 0.50–0.80%, fat 0.28–1.79%, sugar 8.05–10.54%, total titratable acidity 0.47%, crude fibre 0.85–3.60% and vitamin C content 42 mg/100 g of raw pulp. Ishak *et al.* (2005) found the fruit to contain fat (0.34–0.54%), protein (1.76–2.33%) and ash (6.23–6.78%) and 4.65–5.86 mg/100 g vitamin C. It is a good source of iron and contains higher levels of phosphorous than sodium, magnesium, calcium and zinc (Ishak *et al.*, 2005). Unripe fruits contain 9.76% pectin (Morton, 1961) which is useful as a food additive for its gelling properties (Koubala *et al.*, 2008). The total phenol content of golden apple or ambarella (33 ± 5 mg/100 g) is lower than that of orange (75 mg/100 g), but is similar to that of mangosteen, banana, water apple,

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papaya and dragon fruit (Lim *et al.*, 2007). The consumption of fresh golden apple fruit is useful against diabetes mellitus, indigestion, urinary tract infections, hypertension and hemorrhoids (Morton, 1961).

8.2 Fruit development and postharvest physiology

8.2.1 Fruit growth, development and maturation

Graham *et al.* (2004b) published growth and developmental changes for fruit of the miniature golden apple. They documented that the miniature golden apple fruit exhibited a single sigmoid growth curve based on values for fruit length, diameter and fresh mass. During early stages of growth after fruit-set, fruit growth was very rapid with major increases in fruit length for up to 11 weeks and continued increases in fruit diameter and fresh mass for an additional two weeks. They concluded that the exponential growth phase lasted for up to about 13 weeks after fruit-set. This phase was followed by a phase of relatively constant values for length, diameter and fresh mass which lasted from 13–23 weeks after fruit-set. It was found that harvest maturity or the mature-green stage was attained at 19–21 weeks after fruit-set as indicated by constant fruit mass of 64–68 g.

The traditional large type golden apple fruit trees have fruits with an average weight of 140–224 g, fruit length of 7.5 cm and width of 6.3 cm (Bauer *et al.*, 1993). However, fruits in Grenada and St Vincent in the Caribbean have been observed to weigh as much as 450 g (Winsborrow, 1994). Franquin *et al.* (2005) characterized mature-green fruits grown in Martinique (French West Indies) with average length, diameter and weight being 71 mm, 54 mm and 116.5 g respectively.

8.2.2 Respiration, ethylene production and ripening

The respiratory patterns during growth and development for both fruit types are typical of a climacteric fruit (Graham *et al.*, 2004a; Daulmerie, 1994). For miniature golden apple fruits Graham *et al.* (2004a) indicated that the initiation of a climacteric rise in respiration occurred at 21–23 weeks after fruit-set, when colour break was observed and ripening progressed thereafter. Some 85–100% of miniature golden apple fruits fell from the plants between maturation and ripening. No ethylene was detected in fruit up to colour-break, while still attached to the plant. However, once detached, fruit ripened rapidly with the production of ethylene and much increased respiration rates within 2–5 days. On the initiation of fruit ripening, there were major declines in fruit firmness and starch, total titratable acidity (TTA) and vitamin C contents. These changes were accompanied by considerable increases in total and reducing sugar contents, soluble solids concentration, pH and sugar-acid ratios (Fig. 8.1, Table 8.1). Organoleptic tests indicated that miniature golden apple fruits received acceptable ratings for flavour and texture when harvested 19–23 weeks after fruit-set.

For miniature golden apple fruits at the exponential growth phase Graham *et al.* (2004b) noted a decline in respiration rates with increased fruit development,

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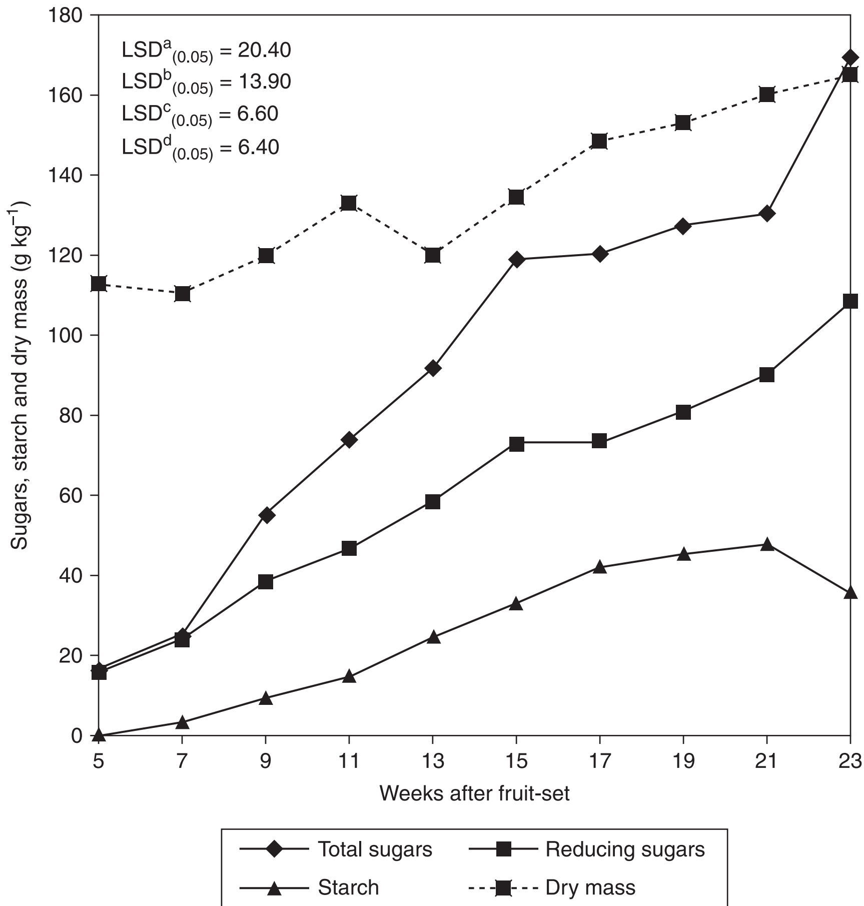

Fig. 8.1 Changes during the growth and development of miniature golden apple fruit. Total sugars, reducing sugars, starch and dry mass. LSD: a = total sugars, b = reducing sugars, c = starch, d = dry mass. Level of significance was ($P < 0.001$) for starch, total and reducing sugars ($P < 0.01$) for dry mass (Graham *et al.*, 2004).

from approximately 52.61 mg $kg^{-1}hr^{-1}$, five weeks after fruit-set to about 25.45 mg $kg^{-1}hr^{-1}$ eight weeks later. The high rate of respiration detected during the early stages of fruit development was likely to be related to intense cellular activity, particularly high rates of cell division, cell enlargement and cell differentiation in the tissue of the developing fruit, as observed in other fleshy fruits (Enamorado *et al.*, 1995). Respiration rates which declined throughout the exponential growth phase continued to decline and attained a pre-climacteric minimum of 17.25 mg $kg^{-1}hr^{-1}$ four weeks later at colour-break.

Only miniature golden apple fruit harvested at earliest 19 weeks after fruit-set developed the changes characteristic of proper ripening. Fruit ripened fully within 5–7 days at 32 °C with the development of a deep yellow to orange skin colour

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Table 8.1 Compositional changes in miniature golden apple fruit during growth and development (Graham *et al*., 2004)

Weeks after fruit-set	SSC (g kg^{-1})	TTA (g kg^{-1})	.pH	Vitamin C (g kg^{-1})	Sugar acid ratio
5	65.80ay	15.80b	2.48a	0.05a	4.16a
7	83.30bc	18.10a	2.53a	0.08b	4.61ab
9	69.20a	14.80bc	2.67b	0.09b	4.68ab
11	75.00ab	14.50bc	2.71b	0.08b	6.50c
13	70.00ab	13.60cd	2.68b	0.09b	5.16b
15	78.30ab	12.40de	2.72b	0.09b	6.31c
17	73.30ab	11.00e	2.75b	0.11c	6.66c
19	75.00ab	7.10f	2.77b	0.10bc	10.56d
21	75.00ab	6.80f	2.89c	0.14d	11.03d
23	93.30c	6.70f	3.01d	0.09b	13.93e

[y] Means followed by the same letter(s) are not significantly different ($P < 0.05$).

and soluble solids concentration of between 120 to 130 g kg^{-1}. In contrast, fruit harvested earlier developed a pale yellowish skin colour and peak soluble solids concentration of 100 g kg^{-1}. Such findings showed that at stages prior to 133 days, fruit was immature and that the mature-green stage of development was attained in fruit older than 132 days after fruit-set (Graham *et al.*, 2004a).

In another investigation Graham *et al.* (2004c) examined the changes in respiration, ethylene production rates and physicochemical quality attributes of miniature golden apple fruits during storage at 21 °C and 31 °C at three stages of maturity (Fig. 8.2). The number of days that fruit took to attain full skin colour development associated with ripening varied with storage temperature and stage of development. Accordingly, at 21 °C and 31 °C respectively, immature fruit took 8 and 6 days, mature-green fruit 10 and 8 days and breaker fruit 7 and 6 days. At both temperatures increased skin colour was associated with a climacteric pattern of respiration and higher soluble solids concentration and total sugar content. Generally, at the climacteric, simultaneous peaks in CO_2 and C_2H_4 (ethylene) production were obtained for breaker fruit after 7 days but after 8 days for both immature and mature-green fruit. Storage at 21 °C delayed the initiation of climacteric CO_2 production by immature fruit and the initiation of climacteric C_2H_4 production by both mature-green and breaker fruit (Graham *et al.*, 2004b).

Daulmerie (1994) investigated postharvest respiratory activity of the fully mature large type golden apple fruit under ambient conditions (28 °C) over a 12 day period. A typical climacteric pattern of respiration was 24 m/kg^{-1} hr^{-1} which decreased rapidly to 15.5 m/kg^{-1} hr^{-1} by day 3 and the fruits were still green. Beyond this period up to day 7, noticeable changes in the green skin colour to light cream colour were visible. The climacteric rise was initiated then, after which CO_2 levels increased dramatically from 19 m/kg^{-1} hr^{-1} to 35 m/kg^{-1} hr^{-1} after 9 days when fruits were ripe and coinciding with the climacteric peak. The decrease in CO_2 to 24 m/kg^{-1} hr^{-1} on day 10 represented the climacteric

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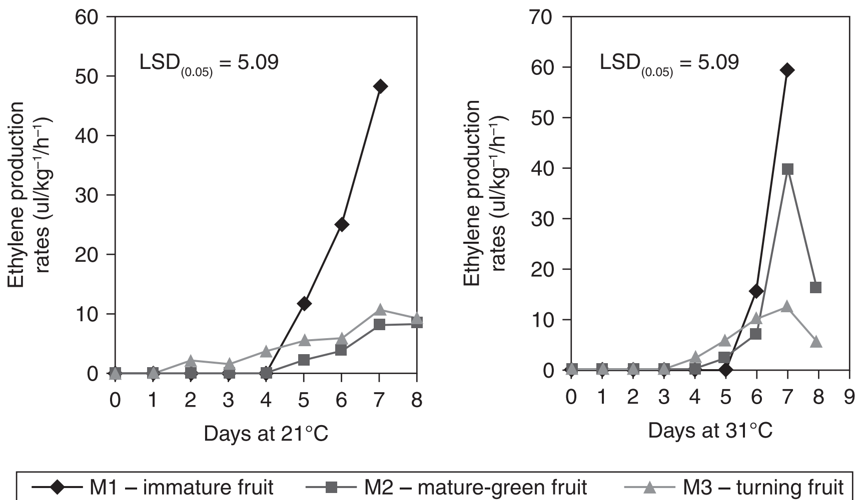

Fig. 8.2 Ethylene production of miniature golden apple fruits at three stages of fruit maturity during storage (Graham *et al.*, 2004).

decline or post-climacteric. Evidence of over-ripening was noted after 11 days at 28 °C.

Daulmerie (1994) presented theories to account for the apparent delay of golden apple fruits (large type) to undergo ripening while attached to the parent tree. One theory suggested that an unknown inhibitor is probably produced in the tree which migrates into the fruit while it is still attached thereby preventing the fruit from reacting to ripening inducers such as ethylene. Another explanation is that ripening of golden apple fruit is possibly activated by fungal growth and perhaps the inhibitor is metabolized by the fungus.

Both the large and small fruit types are limited by a short shelf life after harvest, particularly due to the high rates of respiration and rapid rate of ripening at ambient conditions. Ethylene regulates the ripening process of this fruit; thus the ripening process can be reduced by inhibiting ethylene biosynthesis or action (Graham *et al.*, 2004c).

8.3 Maturity indices and quality components

Golden apple fruits of both types, miniature or large, are required by local, regional and extra-regional markets to be mature green, unripe, firm, free from mould surface disease, mostly free from scarring (not more than 15% of the fruit surface) and free from mechanical damage (Mohammed, 2003; Mohammed and Wickham, 1996; Graham *et al.*, 2004c; Daulmerie, 1994). Fruits of both types are oval, round or pear-shaped and this variation in fruit shape can exist in a single cluster of fruit in both genetic lines. For the large fruit a minimum weight and length of 150 g and 6 cm is required compared to the miniature type where a

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minimum weight and length of 60–65 g and 4–5 cm is acceptable for most markets. Mature green fruits are selected on the basis of flesh, skin colour and gloss. Upon maturity, the flesh colour changes from pale green to cream and, on ripening, to yellow. Skin colour changes from deep green with minimal gloss to pale glossy green at maturity, and then to golden yellow at ripening.

8.4 Preharvest factors affecting fruit quality

Golden apple trees grown in the Caribbean islands are usually propagated from non-selected materials and therefore the production and quality of fruits tend to be highly inconsistent (Winsborrow, 1994). Andall and Baldeo (2000) investigated the effect of fruit and inflorescence pruning on fruit size and yield of dwarf golden apple fruits. They concluded that fruit pruning resulted in an increase in fruit size but fruit yield was reduced; inflorescence pruning on the other hand reduced fruit size as well as fruit yield. The golden apple tree is tolerant to drought, but under such conditions the trees remain small and produce fewer undersized fruits (Weir *et al.*, 1982; Morton, 1987). Excessive irrigation may cause the fruits to be soft and bruised (Macia and Barfod, 2000). Full sunlight is required for optimum tree and fruit growth (Popenoe, 1979). However, young trees require light shade for the first few years (Ochse *et al.*, 1961). Generally, sugar content of the fruits depends on the number of hours of exposure to full sunlight (Macia and Barfod, 2000). Thus, ripening of the fruit is best during periods of low rainfall. In Grenada, large and sweet golden apples (*Spondia dulcis*) are produced in the relatively drier regions (Bauer *et al.*, 1993). There is also less gumming and the fruits are clean when there is less rain. However, Bauer *et al.* (1993) also reported that high temperatures during the dry season may cause premature yellowing due to sun scalding. Geurts *et al.* (1986) reported yields per tree of 800–900 fruits with an average total weight of 270–450 kg, but in later investigations Bauer *et al.* (1993) claimed yields as high as 900 kg.

8.5 Postharvest handling factors affecting quality

8.5.1 Temperature management

Golden apple fruits can be classified as having a high rate of respiration comparable to other tropical fruits such avocado and papaya. The rate of respiration and evolution of respiratory heat can be reduced by harvesting fruit at a consistent stage of maturity, handling carefully to minimize physical damage during harvesting, packing, loading and unloading operations, packing in shallow, padded, well-ventilated, light-coloured plastic crates, placing packed fruits in shade or covering fruit-filled harvesting containers with broad leaves such as banana leaves, transporting containers to packinghouse in well-covered, light-coloured tarpaulins, harvesting and packing fruits during cooler parts of the day. Hydrocooling to remove field heat should be undertaken within 45 minutes of arrival at the packinghouse. Submerging fruits in

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tap water (7–10 °C) for one hour is an effective temperature management technique (Mohammed, 1997). Precooled fruits should be kept at a non-chilling temperature of 12–13 °C at a relative humidity of 85–90% throughout the postharvest handling system to optimize quality and shelf life (Mohammed, 2003).

8.5.2 Physical damage

The mature-green golden apples of both genetic lines are dense, firm and turgid and therefore extremely susceptible to all forms of physical damage at every stage of the postharvest handling system. At harvest, the main type of physical damage is due to punctures from the harvester's finger nails. However, the main cause of most of the bruises on the fruits is transportation. Larger bruises usually occur during transport and packaging, due to movement of fruits around the sorting tables, crates and boxes. Overfilling or underfilling of harvesting containers can also induce compression, bruising and abrasions which serve as avenues for secondary infections (Mohammed, 1997). The impact of this physical damage may only become visible at a later stage during distribution and marketing. Cracks, for example, become visible after fruit has been hydrocooled or washed, when water seeps between the thin skin and flesh and eventually forms a watery soft spot culminating in fruit decay.

The need to monitor and implement proper fruit handling to reduce physical damage is paramount. This can be achieved by selection of shallow containers, padded containers and conveyor belts, minimizing fruit rolling and rubbing and wearing gloves during harvest sorting and packing operations. Daulmerie (1994) estimated cumulative postharvest losses arising from physical damages at harvest, during transport and at washing to be 8.4%. Another author estimated that about 41% of fruits are rejected due to bruises that occur during packing, storage and transportation (Daulmerie, 1994).

8.5.3 Water loss

The rate of moisture loss in golden apple fruits is a function of stage of maturity at harvest, storage temperature, relative humidity and storage duration. Graham *et al.* (2004b) reported percentage fresh weight losses of miniature golden apple fruits at immature, mature-green and breaker stages over a 14-day period at 9 °C, 21 °C and 31 °C respectively. At all temperatures fresh weight losses were highest for immature followed by mature-green and lowest for breaker fruits. At all temperatures over 14 days fresh weight losses averaged 5.6% and no visible evidence of shriveling was observed. Likewise, Daulmerie (1994) did not observe shriveling in the large type fruit even at 12% fresh weight losses, but in this study, fresh weight losses decreased with storage temperature. Modified atmosphere packaging also contributed to a 50% weight loss reduction compared to control fruits. Daulmerie (1994) found that fruit stored in sealed polyethylene bags lost less percentage volume compared to fruit stored in air. Daulmerie (1994) claimed that changes in fresh weight resulting in shriveling of fruits stored at 8 °C and the associated symptoms of pitting, mummification of fruits and holes arising from the collapse of the cells beneath the

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surface were due to CI. Mohammed and Wickham (1997), however, contradicted this claim, indicating that symptoms associated with desiccation were different from those of chilling injury. In their study golden apple fruit appearance was affected by extensive shriveling and development of longitudinal depressions and water-soaked areas. After 3 days at 30 °C golden apple fruits stored in paper bags (control) had lost 4.08% of their fresh weight; the loss had increased two-fold 8 days later. The fruit reached the end of its shelf life after 11 days at 30 °C with rapid decay, the major symptom being dry rot, caused by *Fusarium* sp.

8.5.4 Atmosphere

Mohammed and Wickham (1997) reported that the altered atmosphere created by waxing and seal-packaging golden apple fruits markedly influenced CI damage, percentage marketable and percentage decayed fruits during storage (Table 8.2). They concluded that waxing was more effective than low density polyethylene (LDPE) bags in alleviating CI damage in golden apple fruits. Visible symptoms of CI for waxed fruits were observed after 23 days at 5 °C while those of LDPE packaged fruits were noticeable after 19 days. Waxing also accounted for 8% and 6.3% more marketable fruits after 19 and 23 days at 5 °C than LDPE packaged fruits. Percentage decayed fruits after 23 days at 5 °C was 4.1% less for waxed compared with LDPE packaged fruits. When fruits from these two treatments were transferred for 1 day storage at 30 °C waxed fruits had lower incidences of CI, pitting and decay than LDPE packaged fruits. Decay of fruits in LDPE bags from these treatments was enhanced as a result of condensation within the sealed bags and the warmer temperature obtained upon transfer to 30 °C. Bacterial soft rot caused by *Eirwinia* sp. dominated these samples.

Table 8.2 Effect of packaging and waxing upon percentage marketable and decayed golden apple fruits after 19 and 23 days

Treatments	Marketable fruits (%)		Decayed fruits (%)	
	19 days	23 days	19 days	23 days
LDPE @5°C	26.6	10.6	11.1	16.2
LDPE @5°C + 1 day @30°C	22.1	6.6	27.2	36.0
Wax @5°C	34.6	16.9	10.0	12.1
Wax @5°C + 1 day @30°C	26.6	8.2	26.7	30.0
Paper bags @5°C	0.0	0.0	84.9	86.2
Paper bags @5°C + 1 day @30°C	0.0	0.0	100.0	100.0
Paper bags @30°C	0.0	0.0	94.9	100.0
$LSD_{(0.05)}$	4.1	1.4	4.49	4.0

LDPE: Low density polyethylene
Source: Mohammed and Wickham (1997)

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8.6 Physiological disorders

8.6.1 Chilling injury

Mohammed and Wickham (1997) investigated the effects of modified atmosphere packaging, storage temperature and duration on the keeping quality and chilling-tolerance of large type golden apple fruits. They confirmed that golden apple fruits are very chilling-sensitive when stored at 5 °C. Fruits stored in paper bags at 5 °C for 7 days showed visible symptoms of CI with tiny randomly scattered pits, but after 11 days CI was more severe, as the tiny pits coalesced to form a more concentrated pattern resulting in larger depressed areas characterized by a definite dark-brown discoloration (hereafter referred to as sheet pitting). The injury became even more apparent in fruits stored for as little as 3 days at 5 °C which were then subsequently stored for an additional day at 30 °C. The sheet pitting increased in severity and affected areas became water soaked with individual flat or sunken spots surrounded by a small ring of normal tissue. Viewed together, these areas had a dappled appearance. As levels of water loss increased further, the sheet-pitted areas became irregularly sunken with a pebbly and grainy appearance. Mohammed and Wickham (1997) demonstrated that waxing delayed the appearance of pitting in the above storage regimes to days 23 and 15 respectively (Table 8.3). They also showed that the skin pitting that developed in fruit packaged in LDPE bags after 19 days at 5 °C became more pronounced after the fruit was held at 30 °C for a further day. Despite the time taken for symptoms to appear, measurements of bioelectrical

Table 8.3 Effect of packaging and waxing upon bioelectrical resistance (kilohms) of golden apple fruits during storage

Treatments	Bioelectrical resistance (kiohms)							
	Storage period (days)						Statistical significance	
	3	7	11	15	19	23	$LSD_{(0.05)}$	Linear
LDPE @5°C	70.00z	45.34	42.89	39.89	38.23	34.78	3.53	*
LDPE @5°C + 1 day @30°C	66.61	41.26	36.41	35.61	27.20	20.14	6.04	*
Wax @5°C	69.00	46.77	44.00	39.80	35.80	30.33	3.90	*
Wax @5°C + 1 day @30°C	64.34	41.27	36.11	30.14	25.16	17.61	3.11	**
Paper bags @5°C	63.90	38.00	27.40	25.77	26.77	23.97	2.43	*
Paper bags @5°C + 1 day @30°C	56.66	37.41	24.41	20.10	ND	ND	3.00	**
Paper bags @30°C	74.67	51.53	36.00	ND	ND	ND	7.92	*
LSD(0.05)	3.53	1.01	7.68	4.01	1.40	2.29		

[Z] Mean of 10 fruits/treatment × 4 replicates
LDPE: Low density polyethylene
Source: Mohammed and Wickham (1997)

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resistance and electrolyte leakage indicated that severe membrane damage had occurred by 7 days storage at 5 °C using all packaging methods mentioned above (Tables 8.4 and 8.5). The inverse relationship encountered for bioelectrical resistance (BER) and electrolyte leakage (EL) provided a useful objective measure of the onset of CI prior to the appearance of CI symptoms. They argued that fruit ripening and senescence initiated and contributed to the loss in membrane integrity.

Table 8.4 Effect of packaging and waxing upon electrolyte leakage (%) of golden apple fruits during storage

Treatments	Electrolyte leakage (%)							
	Storage period (days)						Statistical significance	
	3	7	11	15	19	23	$LSD_{(0.05)}$	Linear
LDPE @5°C	16.01	18.18	20.18	27.43	46.45	52.47	2.00	**
LDPE @5°C+ 1 day @30°C	16.00	17.60	25.11	33.21	48.16	56.14	7.01	**
Wax @5°C	14.74	20.98	21.18	21.58	29.03	58.61	5.61	*
Wax @5°C+ 1 day @30°C	14.70	24.61	29.23	30.14	35.16	37.19	4.40	*
Paper bags @5°C	15.76	17.53	39.34	52.87	52.89	59.45	4.07	**
Paper bags @5°C+ 1 day @30°C	17.61	21.62	44.66	56.79	ND	ND	10.59	**
Paper bags @30°C	10.94	36.74	32.13	ND	ND	ND	10.17	*
$LSD_{(0.05)}$	1.98	2.48	0.79	3.06	5.01	3.14		

[Z] Mean of 10 fruits/treatment x 4 replicates
LDPE: Low density polyethylene
Source: Mohammed and Wickham (1997)

Table 8.5 Effect of heat treatments on selected quality attributes of miniature golden apple fruits stored at 22°C for 6 days

Heat treatments	Marketable fruit (%)	General appearance[x]	Decay (%)	Anthracnose incidence (%)	Heat injury ratings[y]
46°C for 10 min.	75	4	25	0	1
46°C for 15 min.	0	2	20	0	4
46°C for 20 min.	0	1	20	0	5
49°C for 10 min.	0	1	15	0	5
49°C for 15 min.	0	1	25	0	5
49°C for 20 min.	0	1	30	0	5
Untreated control	35	2	65	25	1

[X] Heat injury ratings: 1 = none, 2 = slight, 3 = moderate, 4 = severe, 5 = very severe.
[Y] General appearance ratings: 1 = very poor, 2 = poor, 3 = fair, 4 = good, 5 = excellent.
Source: Graham *et al*. (2004)

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The change in visual colour from green to yellow accompanied by a distinct high-scented aroma at 30 °C indicative of fruit ripening at an advanced stage was notably absent in chill-injured fruits stored at 5 °C.

Graham *et al.* (2004c) investigated the chilling sensitivity of miniature golden apple fruits harvested at three stages of maturity and stored at 9 °C. Chilling injury symptoms were evident after 4, 6 and 10 days respectively for immature, mature-green and breaker-stage fruit; however, these fruits were stored at a temperature 4 °C higher than the large type fruits used by Mohammed and Wickham (1997). There was an inverse relationship between BER and EL in both miniature and large type fruits as the rate of increase in severity of CI accelerated over time.

8.6.2 Other physiological disorders

Fruits of both genetic lines are susceptible to heat injury. Heat injury symptoms include extensive bruising of the skin and the prevalence of hard lumps in the flesh of ripe fruit. This was reported by Graham *et al.* (2004a) when investigating the effects of hot water treatments prior to storage on the incidence of decay. Fruits heat-treated at 46 °C for 15 or 20 minutes or at 49 °C for 10, 15 or 20 minutes exhibited symptoms consistent with heat injury described above, after 3–4 days or 1 day respectively when stored at 22 °C and were considered unmarketable. However, 75% of fruits heat-treated at 46 °C for 10 minutes were still marketable with no visible evidence of heat injury after 6 days at 22 °C (Graham *et al.*, 2004a) (Table 8.5).

8.7 Pathological disorders

In Jamaica and various other countries the golden apple tree is subject to gummosis and is consequently short-lived (Ochse and Bakhuizen,1977; *Geurts et al.*, 1986; Fortune and Dilbar, 1993, Persad 1996). Various cankers also cause problems, including a resinous canker caused by *Lasiodiplodia* sp. (Ponte *et al.*, 1988) and a bacterial canker caused by a pathogenic form of *Xanthomonas campestris* pv. *Magiferae indica* (Pruvost and Luisetti, 1989; Pruvost *et al.*, 1992). Golden apple fruit has a high rejection rate, which can be attributed to a large extent to a lack of control of disease and pests (Bauer *et al.*, 1993). As the golden apple is not a major crop in the countries in which it is found, there is a lack of attention to its pathological disorders and their control (Geurts *et al.*, 1986). Golden apple fruits of both genetic lines grown in regions of high humidity experience problems associated with anthracnose. Trees cultivated in areas where the average rainfall is 2000 mm and altitude 150 m above sea level are generally smaller in size but experience fewer disease problems (Winsborrow, 1994). Different types of fungi, occurring mainly during the wet season in the Caribbean, are observed on golden apple fruits of both genetic lines. Bauer *et al.* (1993) reported the occurrence of small (8 mm in diameter) round black lesions on green fruit with gumming developing slowly on the fruit as well as other large black spots of 1.5 cm of diameter. These lesions usually remain

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superficial (3 mm deep) and do not cause fruit rotting or softening. When fruits ripen the infected area remains pale green and softens. The spotting incidence increased during the rainy season from June to November and were caused by different types of fungi, such as *Guldnardia* spp., *Asteromella* spp., and *Colletotrichum* spp. (Bauer *et al.*, 1993). Brown lesions with no gumming can be observed on ripe fruits, causing rotting, and are identified as *Colletotrichum gloeosporioides*. A stem rot (*Botryosphaeric* sp.) caused by a bacterium also occurs on ripe fruits (Persad, 1996; Bauer *et al.*, 1993). Sooty mould due to *Tripospermum* sp. is common on the fruit skin (Bauer *et al.*, 1993). Samson (1986) also reported on the incidence of *Phytophthora* sp. A fungus *Sphacelema spondias* was reported to cause round spots on the leaves and fruits in Florida and Brazil (Geurts, 1986). Graham *et al.* (2004a) dipped miniature golden apple fruit in water at 46 °C for 10 minutes and reported effective control of anthracnose infections. Exposing fruits to water at the same temperature for 15 minutes also resulted in no incidence of anthracnose but caused severe heat, rendering the fruit unmarketable.

8.8 Insect pests and control

Both the golden apple fruit and the tree are attacked by various insect pests. Severe caterpillar attacks can result in complete defoliation of trees. The leaves can also suffer from severe damage by specific beetles (Ding Hon, 1978). In Indonesia and Malaysia, the leaves are severely attacked by the larvae of the kedondong spring-beetle, *Podontia affinis* Grond and *Podontia punctata* (Ochse and Bakhuizen, 1977; Guerts *et al.*, 1986; Prihatman, 2000). In India, the first beetles appear in June and defoliate the trees. Eggs, laid in clusters of 20–60, incubate for a period of 7–8 days; the life cycle is 32–35 days. Some parasites of these beetles have been found as a nematode (*Mernis*) and a fungus (*Cephalosporium*). A foliar spray of spores of this fungus, or of 0.25% of malathion, in June/July gave effective control of the insect (Singh *et al.*, 1989). In Costa Rica, the bark is eaten by a wasp, causing necrosis which leads to death. No particular insects or disease have been reported in Florida.

Infestation of fruit by pests during the immature and mature stages will reduce the quality of the fruits due to blemishes on the fruit surface and fruit distortion, making them unmarketable. Bauer *et al.* (1993) reported the presence of scale insects on immature green fruits, primarily on the fruit peduncle and shoulder. Feeding by the scale insects is associated with the development of pale-coloured, light green to yellow spots scattered on the green skin of the fruit. The incidence of scale insects coincided with early fruit development in the dry season and also caused black sooty mould (Plate XV A and B) to be deposited on the green fruits. Bauer *et al.* (1993) also reported mite infestation during the early stages of fruit development which caused scarring with pale-brown to grey bands across the fruit surface which rendered fruits unfit for the export market. Severe mite infestations create corky deposits at the blossom end of the fruit culminating in deformed fruits. The fruit are also vulnerable to the Caribbean fruit flies (Leather *et al.*, 1967; Guertz, 1986).

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Bauer *et al.* (1993) cite the following as other pests of the golden apple tree: ants, termites, epiphytes, birds, beetles and lizards. The arrival of ants has been linked to scale insect infestation, as they are attracted by deposits left by these insects, as well as by the tree's gum and sap. Tree branches are destroyed by termites, and epiphytes are found on trees located in regions of high relative humidity. Pests such as birds, millipedes and lizards are not significant causes of postharvest losses.

8.9 Postharvest handling practices

8.9.1 Harvest operations

The harvest season for the large type fruits according to Bauer *et al.* (1993) is from August until November with the peak season being September and October, but according to Daulmerie (1994), only limited quantities of fruit are available at the beginning and end of the season. Harvesting is done manually and therefore is very challenging and labour intensive, particularly when obtaining fruits from the large type trees as opposed to miniature or dwarf type trees. The traditional large type trees which vary from 6–20 m in height with a trunk 50 cm in diameter demand creative harvesting techniques and devices. Fruits are harvested by climbing or using a picking pole with either a basket or bag attached to catch the fruit. A pouch bag can also be used when climbing or using a ladder. A rope-pulley system can also be used to harvest larger loads. Mechanical devices such as an automatic platform trough could be adopted but these require heavy capital investment and maintenance costs (Mohammed, 2003). These devices are further constrained by their inability to access trees on high or uneven terrains (Medlicott, 1990). After picking, the fruit is sorted and transported to market by light truck or pick-up (Bauer *et al.*, 1993).

Whatever harvesting aid is used, it is critical that fruits are not thrown or dropped to the ground. Golden apple fruits crack or split easily on impact resulting in postharvest losses (Mohammed, 2003). Bauer *et al.* (1993) estimated losses of fruits at harvest in a study conducted in Grenada to be as high as 50% and attributed this to shaking of branches causing fruits to drop on hard surfaces, non-uniform fruit clusters which account for the harvest of premature fruits, difficulty in harvesters reaching fruits at the terminal ends of weak branches, and fruit bruising caused by poor handling, inappropriate containers, overstacking and transportation over rough and hilly terrains. Daulmerie (1994) estimated that the magnitude of postharvest losses at harvest was 9.65% This author suggested that the main causes of rejects at harvest were mite damage, immature fruits due to varying stages of fruit maturity within the same cluster, fungal infestation, deformity and mechanical damages.

8.9.2 Packinghouse practices

Golden apple fruits should be transported in shallow light-coloured plastic crates. These should be carefully loaded and stacked onto truck trays, covered with a

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white-coloured sanitized tarpaulin and taken to the packinghouse. Fruits should be washed in water containing 100–120 ppm sodium hypochlorite solution (Mohammed, 2003). In situations where fruits are harvested with sooty mould, Daulmerie (1994) recommended a postharvest dip of 300 ppm calcium hypochlorite for 15–35 minutes followed by rinsing in tap water. The soaking and washing procedures also remove dirt, surface debris and latex (Medlicott, 1990). Fruits are air-dried prior to packing in cardboard cartons. Fruit are sorted according to size with a minimum length of 6 cm and weight of 140 g (Medlicott, 1990). Insect damage in the form of distinct brown scars must not exceed 15% of the fruit surface. Maximum weight of fruit in boxes should not exceed 18 kg, which represents approximately 150 fruits. Packed fruits must be palletized and fork-lifted into a chill room at 10–12 °C and 90–95% relative humidity. Daulmerie (1994) estimated postharvest losses due to packinghouse operations at 10.5%.

8.9.3 Control of ripening and senescence

Under ambient conditions, golden apple fruit commence ripening 2–4 days after harvest at the full mature green stage, but they ripen slower when refrigerated. Therefore for supply to regional and overseas markets at the mature green stage, fruits need to be stored throughout the marketing chain under refrigerated conditions (10–12 °C, 90–95% rh) to control ripening. Being climacteric, the evolution and presence of C_2H_4 must be managed by ensuring that fruits are not kept with other climacteric fruits that are moderate to high producers of C_2H_4. Proper ventilation and sanitation protocols should be adhered to and the fruit should be sorted carefully to remove damaged fruits which produce C_2H_4. Market demand for fully ripe fruits also exists. To fulfill this demand, mature green golden apple fruit can be allowed to ripen under ambient conditions for 2–4 days or treated with ethrel (500 ppm) at 20–22 °C and 90–95% relative humidity for 1–1½ days and then subsequently stored at 7–8 °C 90–95% relative humidity until retail display and consumption (Mohammed, 2003). Fully ripe fruits stored at 7–8 °C, 90–95% are less sensitive to chilling injury damage than mature green fruit (Mohammed, 2003).

8.9.4 Recommended storage and shipping conditions

Medlicott (1990) recommended air shipments over sea transport. Mature-green golden apple fruits can be stored under ambient conditions for 24 hours prior to shipment, but maintenance at 10–12 °C and 90–95% relative humidity following packinghouse operations and storage optimizes quality and shelf life until arrival and distribution to overseas market outlets. Daulmerie (1994) reported that after harvest, mature-green fruit can be stored for up to two weeks at 13 °C and 90–95% relative humidity. A temperature above 8 °C should be used for storage, otherwise chilling injury will result. Sanitized fruits can be stored for 25 days in shipment at 11 °C in the presence of an ethylene absorber (Daulmerie, 1994). Ripe and overripe fruits should not be mixed with green ones; they produce ethylene which

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increases during ripening. Golden apple fruits should not be stored in the same shipping container with fruits such as passion fruit, banana, plantains and papayas, which are prolific producers of C_2H_4, as the C_2H_4 would promote ripening and senescence. Stacking protocols that promote a uniform flow of cool air in and around shipping loads should be adhered to, and properly sanitized containers should be used for high display quality at overseas destinations. Fruit cartons for the US market should be sealed to prevent fruit-fly contamination.

8.10 Processing

8.10.1 Fresh-cut processing

Fresh mature-green, breaker and ripe miniature and large type golden apple fruit can be used to make fresh-cut or minimally processed products. Unpeeled fruits yield about 70% and 87% edible parts from ripe and green fruits, respectively. During peeling, a fine layer of skin (3–4 mm) is usually removed, thus giving a yield of 45% and 38% for the green and ripe fruit, respectively (Daulmerie, 1994). The fruits are peeled and cut into quarters or halves with the spines and stone intact and eaten as a snack with or without a sprinkling of salt and selected ground or fresh-cut herbs such as shadon beni (*Eryngium foetidum*) and hot pepper (C*apsicum frutescens*). Alternatively, the fruit can be cut into attractive shapes, but this can lead to a very low yield (less than 40%) and is time consuming, thus is only viable if the wasted parts are used for another product (Daulmerie, 1994). Unpeeled fresh-cut golden apple fruits can be sealed-packaged in LDPE bags or in stretch-wrapped styrofoam trays and stored refrigerated at 7–8 °C for a maximum of 18 days. However, fresh-cut peeled or unpeeled fruits can be dipped-blanched in hot water at 55–60 °C for 10–15 minutes and frozen. Frozen pieces can be stored for more than 8 months and subsequently cooked in curry and spices as a supplement to other meals (Mohammed, 2002).

8.10.2 Other processing options

The versatility of both types of golden fruits is reflected in the diverse range of value-added products into which they are processed, some of which have already been commercialized, including kuchelar, sweet and sour pickles, amchar, chutney, jams, jellies, alcoholic and non-alcoholic beverages. Other products, such as canned fruit in syrup, nectars, sauces, pectin extracted from golden apple have the potential for commercialization. Processed fruits could increase the value of the golden apple crop and open up a new market for countries that produce them. In addition, rejected fruits from the expert trade can be used for processing, providing better income for the exporters and farmers.

Franquin *et al.* (2005) investigated the feasibility of making golden apple nectars at 13° Brix. Previous research had indicated that juice extracted from mature-green fruits had a high starch content, which promoted the formation of white sediment in the bottom of the juice container during storage. The starch also

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made the highly desirable olive green colour of the nectar whiter and pasteurization lessened its intensity further. These authors solved these problems using two strategies. Firstly, to degrade the starch and standardize the juice's starch content, the juice obtained after grinding and sieving was treated with an amyloglucosidase enzyme (AMG 300 L) at various concentrations (200 g/t, 700 g/t, 2 kg/t) for 15 minutes at 60 °C after starch gelatinization (64 °C or 72 °C for 15 minutes). Secondly, the treated juice was used to make nectar at 13 ° Brix, using a green powder prepared from golden apple peels to enhance the colour. These new formulations provided the template for the production of less sweet nectars with a green colour closer to that of the fresh fruit.

In a subsequent study, Franquin *et al.* (2008) evaluated the effects of starch and cell wall degrading enzymes from mature-green golden apple fruits on juice residual starch and soluble sugar content. Starch and cell walls from mature-green golden apple fruits were purified and characterized. Starch contained 21.0% amylose, 78.1% amylopectin and 0.9% in other minor compounds. Cell walls represented 2.8% of the edible fresh matter and mainly consisted of highly methylated pectic substances and cellulose. This investigation further demonstrated that hydrolysis of golden apple starch is possible when pectinolysis has occurred before amylolysis treatment, probably because of the fluidification of the medium by pecto-celluloytic enzymes. Pectinex Ultra SP-L was found to be the most efficient preparation with which to degrade golden apple fruit pectins, releasing 80% of the cell wall uronides from 120 mg g^{-1} of purified cell walls within 1 hour at 30 °C and at a pH of 2.7.

In other studies Koubala *et al.* (2007) investigated the potential of golden apple peels as a source of novel pectin for the food industry for use as a gelling agent in jams, confectionery, bakery fillings and as a stabilizer in yoghurts and milk drinks. They used three types of extraction media, hydrochloric acid (HCI), deoinised water or oxalic acid/ammonium oxalate (OAAO) to extract the pectin from dried alcohol-insoluble residues (AIR) of golden apple peels. Their study identified that golden apple skin or peels are a rich source of pectin, yielding up to 30% of the AIR reported. Depending on the extraction method used, uronic acid contents varied from 557–727 mg g^{-1} dry weight. The degree of methylation ranged from 50–58% and the molar masses were in the range 563 000–303 000 g/mol. The study also revealed that since the molar mass and degree of methylation are important parameters in gel-breaking strength, OAAO golden apple pectins could be useful as food additives. Golden apple pectin compared favourably to lime pectins extracted under the same conditions, thereby confirming their commercial significance as 'designer' pectin.

8.11 Conclusions

Golden apple fruits of both genetic lines are extremely susceptible to mechanical damage and innovative technologies are required to limit losses during harvesting, packinghouse operations and distribution at market outlets. Due to the climacteric

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pattern of respiration where the ripening process seems to be regulated by C_2H_4, appropriate C_2H_4 management protocols are necessary. Research into the effects of C_2H_4 antagonists, e.g., Purafil, 1-methylcyclopropene (1-MCP), as well as controlled atmosphere storage and biotechnological procedures would be beneficial. Major emphasis should be placed on the use of mature-green fruit in view of the range of value-added options products that can be made from it. Many cottage-scale producers who represent or are linked to the main manufacturers of value-added golden apple products would also agree that further research into extending shelf life is necessary to make marine shipment more viable in view of the escalating costs of air shipments. Further investigations are required on the commercial extraction of pectins from fruit peel for use as a stabilizer and gelling agent in ice creams, bakery products and confectionery products. Identification, extraction and analysis of enzymes associated with fruit ripening would also be useful to manage softening and textural changes during the ripening process.

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Plate XIII (Chapter 7) Fresh figs are very sensitive to physical damage, one of the main reasons for their short shelf-life.

Plate XIV (Chapter 8) Miniature and large types of golden apple fruits.

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(a)

(b)

Plate XV (Chapter 8) (a) Mature green and ripe golden apple fruits without sooty mould on fruit skin; (b) mature green golden apple fruits with sooty mould covering extensive areas on fruit skin.

(a)

(b)

(c)

Plate XVI (Chapter 9) Berry bleaching symptoms produced by SO_2. SO_2 penetrates around the insertion of berry pedicel in (a) Thompson Seedless; (b) Red Globe berries. SO_2 penetrates through cracks on berries in (c) Red Globe.

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9

Table grape (*Vitis vinifera* L.)

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Abstract: Table grapes produce clusters of berries on deciduous woody vines. The berries are simple non-climacteric fleshy fruits. Currently, 'Thompson Seedless', 'Red Globe' and 'Flame Seedless' are the main cultivars worldwide. The growth period lasts for 100 to 120 days after full bloom, and grapes are harvested with 15 to 17% total soluble solids (TSS) and/or a TSS: titratable acidity ratio greater than 20. Several biotic and abiotic factors cause postharvest deterioration of grapes, particularly when grapes are transported to markets involving a journey of 15 to 40 days. The critical factors involved in postharvest handling and management of table grapes are reviewed and discussed in this chapter.

Key words: *Vitis vinifera*, table grape, physiological disorder, diseases, postharvest handling, sulfur dioxide.

9.1 Introduction

Table grapes are deciduous woody vines, primarily of *Vitis vinifera*, native to the Mediterranean and Central Asia. Grapes are non-climacteric fruits for fresh consumption that botanically are clusters of true berries. Table grape production comprises nearly 30% of the total world grape production. The major grape-producing countries are China (3 800 000 t), Turkey (3 500 000 t), Italy (1 580 000 t), Chile (955 000 t), the US (725 000 t) and Spain (320 000 t).

Table grapes are also produced in tropical and sub-tropical regions of Brazil (431 000 t), Colombia (19 000 t), India (1 000 000 t), Peru (136 000 t), Tanzania (14 000 t), Thailand (40 000 t), Venezuela (11 500 t), and Yemen (163 000 t). In tropical and sub-tropical regions, it is possible to extend the cropping cycle so that harvesting can occur for 5 to 12 months of the year (Pommer, 2006; Possinhan, 2008).

The objective of this chapter is to review and discuss the critical factors involved in postharvest handling and management of table grapes.

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9.2 Table grape cultivars

More than 50 table grape cultivars are known. The cultivars are grouped by color and by the presence or absence of seeds. Market life varies among cultivars and is also strongly affected by field management, postharvest temperature management and susceptibility to decay.

Currently, 'Thompson Seedless', 'Red Globe' and 'Flame Seedless' are the main cultivars worldwide. However, 'Barlinka', 'Regal Seedless', 'Sunred Seedless', 'Muscat Supreme', 'Victoria' and 'Majestic' are important table grape cultivars in South Africa (Greyling, 2007); 'Blush Seedless', 'Christmas Rose', 'Dawn Seedless', 'Fantasy Seedless', 'Marroo Seedless', 'Muscat Hamburg' and 'Waltham Cross' are commonly grown in Australia; and 'Shami', 'Zeni', 'Dabuki' and 'Betuni' are table grapes commonly cultivated in Israel. The main postharvest characteristics of some cultivars are summarized in Table 9.1.

Table 9.1 Maximum storage time, main deterioration factors and origin of table grape cultivars stored at 0°C

Cultivar	Maximum storage time at 0°C (days)	Deterioration factors	Origin
Thompson Seedless	60	Decay (high), hairline, shatter	
Red Globe	100	Decay (low), dehydration	University of California, Davis (USA)
Flame Seedless	40	Decay (moderate), splitting, dehydration	University of California, Davis (USA)
Superior Seedless	60	Decay (high), skin browning, shatter, dehydration	Sunworld (CA, USA)
Italia	100	Decay (low), skin and flesh browning	
Perlette	40	Decay (moderate), skin browning	
Crimson Seedless	150	Decay (low), dehydration	USDA (CA, USA)
Ribier	100	Decay (moderate), splitting	
Princess	60	Decay (low), skin and flesh browning	USDA (CA, USA)
Barlinka	100	Decay	South Africa
Regal Seedless	60	Decay (low), skin and flesh browning	ARC Nietvoorbij Research Institute (South Africa)
Midnight Beauty		Decay (high), splitting	Sunworld (CA, USA)
Autumn Royal	60	Decay (high), splitting, shatter[1]	USDA (CA, USA)

Note:
[1] Shatter starts from the berry insertion within the cluster

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9.3 Fruit anatomy

Grapevines form berries, which are simple fleshy fruits each produced from a single ovary, after the fusion of two carpels surrounded by the ovary wall that ripens into an edible pericarp. Each carpel can contain two seeds in seeded cultivars or seed traces due to ovule abortion in seedless (stenospermocarpic) cultivars. Berries are developed as a part of the cluster inflorescence composed of a rachis as the main herbaceous axis and two prominent and three or four smaller rachis ramifications. Clusters are attached to the vine by the peduncle, and each berry is attached to the cluster by a pedicel. The proportions of berries and rachis are 97% and 3%, respectively (Fig. 9.1).

Berries are composed of exocarp (skin), mesocarp (flesh) and endocarp (tissue around seeds) tissues plus an external protective cuticle (Fig. 9.1). The exocarp comprises the epidermis and hypodermis. The epidermis is 6.5 to 10 μm thick and is composed of six to ten cell layers of small, thick-walled cells (Considine, 1982). The hypodermis exhibits periclinal and anticlinal growth, allowing three-dimensional enlargement of the berry. The berry pigments (anthocyanin, carotene and chlorophyll), flavor and aroma compounds are accumulated in the epidermal cells.

Initially, the skin of the grape contains stomata, but as the berry matures the stomatal density decreases to less than one stoma per mm^2 (Blanke and Leyhe, 1987), and suberized lenticels remain at the end of the fruit growing stage. Therefore, berry water loss occurs mainly through the cuticle.

Mesocarp accounts for almost 80% of berry weight and consists of 25 to 30 layers of cells with large vacuoles containing the liquid phase. Inside the berry, 10

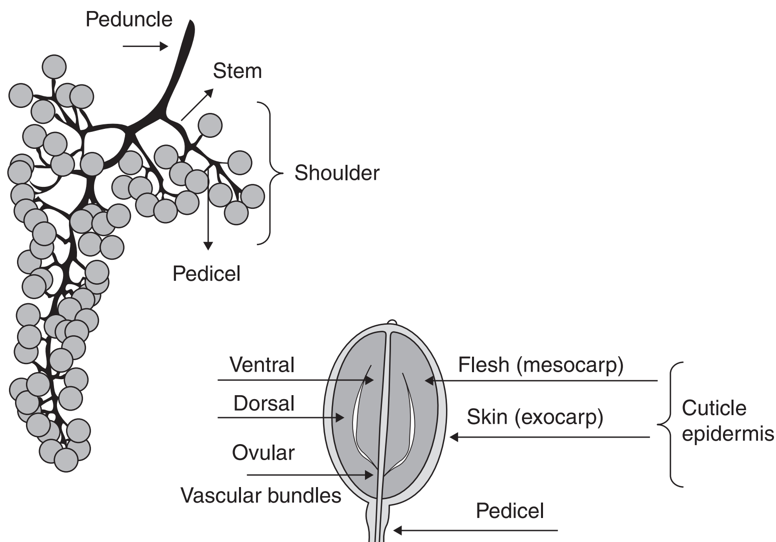

Fig. 9.1 Cluster and berry components of table grape.

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to 12 vascular bundles (xylem and phloem tissues) are found; these are often divided into axial bundles, which feed the central and peripheral areas of the berry.

The cuticle is composed of cutin, waxes and soluble lipids. Cutin is a continuous insoluble polymer matrix (22%) mostly composed of C16 and C18 hydroxy fatty acid esters (Riederer and Schreiber, 2001). The waxes consist of oleanolic acid (79%), a complex mixture of highly hydrophobic soluble materials, including C24 and C30 alcohols and traces of esters, fatty acids, aldehydes and paraffin. The formation of the cuticle begins about three weeks before anthesis as a highly organized tissue. The cuticle thickness ranges from 1.6 to 3.8 μm, and the cuticle content decreases during ripening (Rosenquist and Morrison, 1988). The cuticle is the main barrier limiting transport, respiration and water loss and conferring resistance to decay fungi (Casado and Heredia, 1999; Mlikota Gabler *et al.*, 2003; Zoffoli *et al.*, 2009b).

9.4 Physiology of berry growth and maturation

Berry growth extends for 100 to 120 days after full bloom (DAFB) depending on the cultivar, and three stages of ovary development can be recognized: berry formation (Phase I), a stationary lag stage (Phase II) and berry maturation (Phase III) (Fig. 9.2).

Phase I (berry formation) extends for almost 40 days, triggering the shape and potential size of the berry. It starts at fruit set, after anthesis, and is followed by periclinal and anticlinal cell division for fewer than 20 DAFB. The chlorophyll

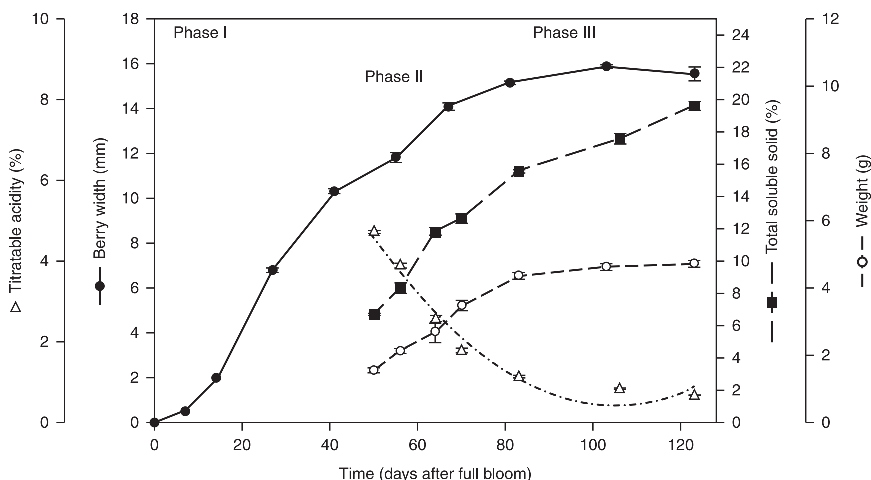

Fig. 9.2 Berry development, accumulation of soluble solid and tritatable acidity of 'Thompson Seedless' table grape in Central Valley of Chile. Data from Zoffoli, 2009, unpublished.

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content increases and 69 to 92% of the total organic acids, mainly malic acid and tartaric acid, contained in the grape berries at maturity are synthesized during this stage (Kliewer, 1966). A high respiration rate and high metabolic activity occur in Phase I, and the berries are firm with skin extensibility remaining relatively low and constant (Matthews *et al.*, 1987). Seeds achieve their full size at the end of Phase I.

Phase II (stationary lag stage) is characterized by a lack of growth. It is shorter in duration in seedless than in seeded cultivars; it is also shorter in early maturity and early flowering cultivars than in late maturity, late flowering cultivars. In Phase II, embryos develop rapidly, reaching their maximum size at the end of this lag phase. A high concentration of indoleacetic acid (IAA) and gibberellic acid (GA) and synthesis of cytokinins (CK) also characterize Phase II (Coombe and Hale, 1973).

Phase III (berry ripening) is characterized by many metabolic syntheses and degradations. Cell wall degradation increases deformability and allows cell expansion with a rapid uptake of total soluble solids (TSS). Malic acid decreases, tartaric acid remains stable, and the synthesis of new phenolic compounds, associated with berry quality, occurs. A better balance between flavor and aroma is developed during Phase III. In red and black cultivars, the red color is obtained at the end of this period as a result of the accumulation of anthocyanins. Chlorophyll degradation starts, allowing carotenoid pigments to be expressed in white cultivars. The titratable acidity decreases from 2.0 to 1.5% at veraison to 0.7 to 0.5% at maturity, in high-acid (e.g., 'Thompson Seedless') and low-acid (e.g., 'Red Globe') cultivars, respectively. The hexoses, glucose and fructose are the major solutes that account for most of the dry matter content of the berry and are accumulated at maturity. Growth regulators like IAA, GA and CK remain low at ripening; however, the concentration of abscisic acid (ABA) increases at the beginning of Phase III (Coombe, 1960; Downton and Loveys, 1978).

Grape is a non-climacteric fruit with a relatively low respiration rate (3–4 mL CO_2 kg^{-1} h^{-1}, at 5 °C). At 5 °C, grapes produce 50% less heat of respiration than other non-climacteric fruits such as sweet cherry (7–9 mL CO_2 kg^{-1} h^{-1}) and 30% less than a climacteric fruits such as apple (5–7 mL CO_2 kg^{-1} h^{-1}). The relationship between respiration rate and temperature in grape, apple and sweet cherry expressed as heat production is indicated in Fig. 9.3. Comparison of the cluster components indicates that the respiration rate of the rachis alone is approximately 15 times higher than that of the berry at 4 °C (Gardea *et al.*, 1994).

Grapes are classified as non-climacteric fruits based on the very small amounts of ethylene produced during berry development. There is a peak of ethylene production at bloom followed by a decreasing concentration until harvest (Weaver and Singh, 1978). However, a small rise in ethylene production has been detected at veraison (Coombe and Hale, 1973). Although the direct effect of ethylene has not been demonstrated in grapes, the application of an ethylene-releasing compound, e.g., ethephon (2-chloroethyl phosphonic acid), at the beginning

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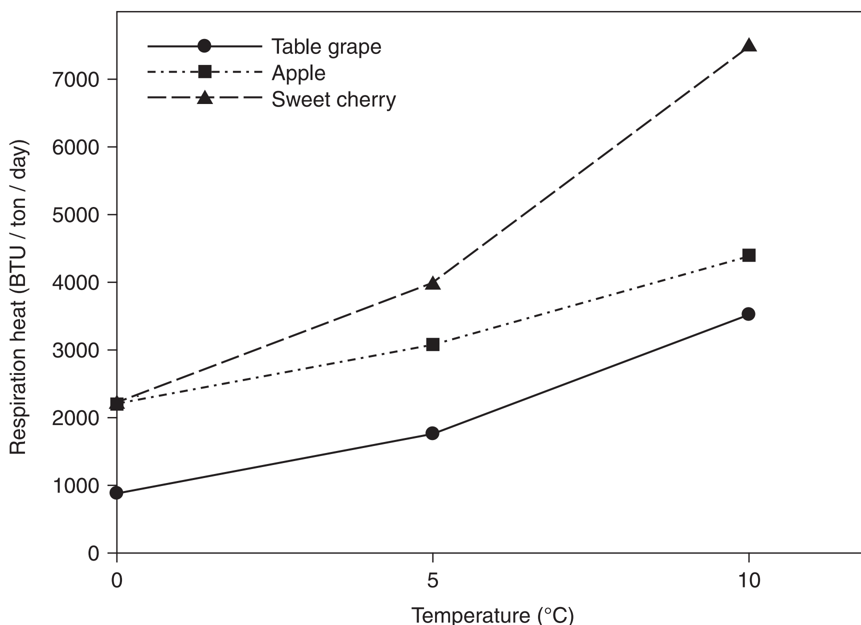

Fig. 9.3 Respiration heat (BTU/ton/day) produced from apple, sweet cherry, table grape at 0, 5 and 10°C (adapted from Postharvest Technology, Research and Information Center: Produce Fact, http://postharvest.ucdavis.edu/Produce/Producefacts/index.shtml).

of verasion enhances color development in red and black cultivars, increases TSS, reduces acidity and firmness and induces berry abscission (Jensen *et al.*, 1975).

It has been postulated that endogenous abscisic acid (ABA) levels in the flesh may mediate the response to exogenous or endogenous ethylene (Coombe and Hale, 1973). Therefore, ABA could accumulate to a certain threshold level, acting synergistically with ethylene in promoting berry ripening. Applications of ABA at veraison enhance color development and maintain postharvest quality of 'Crimson Seedless', 'Flame Seedless' and 'Red Globe' grapes without the negative effect produced by ethephon during storage (Cantín *et al.*, 2007). Therefore, ABA is an effective alternative to ethephon for enhancing the color and maintaining the postharvest quality of red cultivars of table grapes (Peppi *et al.*, 2006; 2007).

Grape maturity is determined commercially on the basis of berry color, TSS and titratable acidity (TA). Depending on the cultivar, grapes are harvested when berries reach at least 15 to 17% TSS with a TSS:TA ratio greater than 20.

9.5 Deterioration factors

Biotic and abiotic factors cause grape deterioration during harvest, transport, storage and commercialization, particularly when grapes have to be transported

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for 15 to 40 days to reach the markets. To reduce the risk of deterioration by biotic and abiotic factors, an integrated approach to grapevine management should be followed at the vineyard. The application of correct cultivation and vineyard practices and the prevention of decay development by the use of fungicide treatments and canopy management near harvesting are of utmost importance, especially if the weather conditions favor decay development.

Careful handling during harvesting and packing to minimize injuries, and hence infections, is a prerequisite for reducing decay development during storage. Temperature management (forced air cooling and storage at −0.5 °C) is crucial for decay control and essential for the maintenance of high-quality grapes during transport, storage and commercialization. Similarly, the use of sulfur dioxide (SO_2) has become an integral part of decay control on grapes intended for short-, medium- or longer-term storage (Fourie, 2008).

Pre- and postharvest decay of grapes can cause considerable financial loss for producers, affecting the grape trade. Several biotic and abiotic agents can limit production, storage and commercialization of grapes. Among the biotic agents, *Botrytis cinerea* is the main cause of postharvest decay. However, other filamentous fungi, e.g., species of *Aspergillus*, *Cladosporium*, *Penicillium* and *Rhizopus* as well as some bacteria and yeasts can be of primary importance under specific storage conditions. Similarly, several abiotic factors (e.g., dehydration, hairline, shatter, splitting and nutritional disorders) can considerably reduce the trade value of table grapes.

9.5.1 Biotic factors

Gray mold

Gray mold decay (*B. cinerea*) is a major cause of pre- and postharvest decay of grapes that affects several other unrelated hosts worldwide. It is characterized by a soft and watery decay that can affect the entire berry. Initially, a loosening of the berry skin (slip-skin) is seen, followed by a brown to reddish discoloration. A white mycelial and abundant gray sporulation (conidia) cover the berry surface, particularly under humid conditions. Conidia are disseminated by winds, rains and eventually some insects can disseminate this fungus in the vineyards. It has been postulated that *B. cinerea* can infect immature berries, remaining latent until berry maturation; however, this infection appears to be rare. Nevertheless, *B. cinerea* can colonize senescent floral debris at flowering, which can provide an inoculum for berry infection after veraison or even in cold storage. Berry infection occurs predominantly at the basal end, rarely at the stylar end, or sometimes by direct penetration of the cuticle at the berry cheek (Fig. 9.4). Aerial mycelia and conidia can spread gray mold from infected to healthy berries. Thus, a single infected berry can spread the infection to an entire package, developing a nest of gray mold even if grapes are stored at −0.5 to 1.0 °C (Coertze *et al.*, 2001; Holz *et al.*, 2003; Latorre and Vásquez, 1996). The incidence of berry infection increases with increasing durations of wetness at temperatures between 12 and

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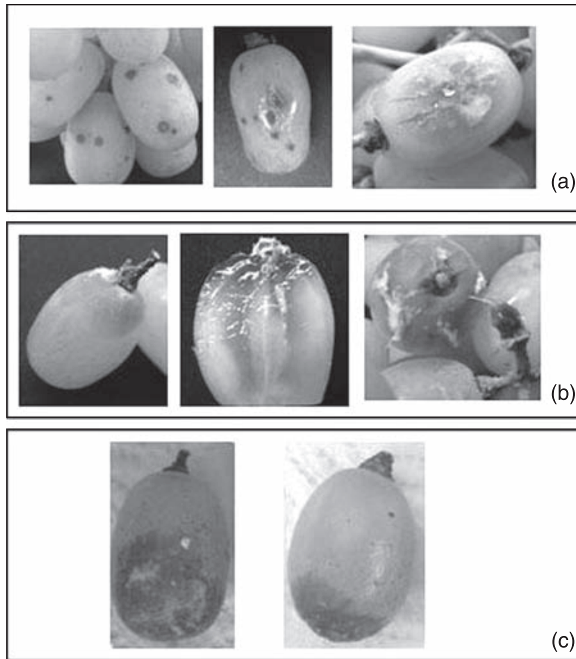

Fig. 9.4 Symptoms of gray mold caused by *Botrytis cinerea* on table grapes (*Vitis vinifera*) cv. 'Thompson Seedless': (a) small necrotic spots at the cheek of the berry; (b) brown discoloration at the base of the berries; (c) brown discoloration at the stylar end.

30 °C, but it is accepted that at least 6 h of wetness are needed at 15 to 25 °C for infection. No infection occurs under dry conditions (Broome *et al.*, 1995; Latorre and Rioja, 2002; Latorre *et al.*, 2002a; Nair and Allen, 1993). Prediction models based on biological, microbiological and molecular methods have been proposed to estimate the risk of gray mold infection at harvest and during storage of table grapes (Cadle-Davidson, 2008; Harvey, 1955; Zoffoli *et al.*, 2009b). Gray mold can be efficiently controlled after harvest by the use of SO_2 and refrigeration (−0.5 °C). However, to achieve a high degree of control during storage and transportation, it is essential to integrate cultural practices and sanitation with chemical control in the vineyard.

Blue mold

Blue mold decay (*P. expansum*) is distributed worldwide, causing soft rot on grapes, apples, pears and other fruits during cold storage. It is characterized by a light brown discoloration of the skin followed by a soft and wet rot that can rapidly affect the entire berry. On the surface of rotted berries, blue-green mold colonies, with or without synnemata, may appear. An internal watery breakdown often occurs in grapes stored for several weeks at 0 °C. Mycelial growth of

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P. expansum can be considerably arrested, but not totally inhibited, at 0 °C. Blue mold infections can be initiated in the vineyard, at the packinghouse or during storage, and they are always associated with wounded fruits. Conidia are disseminated by wind, and contact of infected grapes with healthy ones efficiently spreads blue molds, forming a nest of moldy grapes (Franck *et al.*, 2005; Donoso and Latorre, 2006).

Cladosporium rot

Cladosporium rot (*C. cladosporioides*, *C. herbarum*), although initiated in the vineyard, occurs as a minor wound-associated disease in grapes after a long period (>60 days) of cold storage. It is characterized by the development of dark green necrotic lesions with a velvety appearance that affect only the uppermost part of the berries; eventually the lesions invade sub-epidermal tissues but never the mesocarp. Mycelial growth of *C. cladosporioides* and *C. herbarum* can be considerably arrested, but not totally inhibited, at 0 °C (Briceño and Latorre, 2008).

Rhizopus rot

Rhizopus rot (*R. stolonifer*, also known as *R. nigricans*) usually starts at the base of mature berries as a soft, very watery rot that partially or completely decays infected berries. Longitudinal fissures are produced, and a black mold develops along the fissures. The skin of the berry turns light gray. Infection is always associated with injured berries under warm weather conditions during harvest. Infection caused by *R. stolonifer* may be followed by sour rot organisms (yeasts or acetic acid bacteria). Rhizopus rot can be arrested totally if grapes are stored below 4 °C (Guerzoni and Marchetti, 1987; Latorre *et al.*, 2002b).

Aspergillus rot

Aspergillus rot (*A. carbonarius*, *A. niger*) produces water-soaked brown lesions on wounded berries, followed by dark, black sporulation (conidia). It is primarily associated with warm weather conditions in the vineyard, and it can be arrested totally if grapes are rapidly cooled and kept below 4 °C. Aspergillus rot is often associated with sour rot organisms (yeasts or acetic acid bacteria) (Guerzoni and Marchetti, 1987; Kazi *et al.*, 2008; Latorre *et al.*, 2002b; Rooney-Latham *et al.*, 2008).

Other decay fungi

Other filamentous fungi that have been reported to cause grape decay include *Alternaria alternata*, *Botryodiplodia theobromae*, *Cladosporium sphaerospermum*, *Colletotrichum acutatum*, *C. gloeosporioides* (*Glomerella cingulata*), *Diplodia natalensis*, *Elsinöe ampelina*, *Guinardia bidwelli* (= *Greeneria uvicola*), *Melanconium fuligineum*, *Monilia fructicola*, *Pestalotiopsis menezesiana*, *P. uvicola*, *Phomopsis viticola*, *Pilidiella diplodiella* (= *Coniella diplodiella*), *Rhizopus arrhizus* var. *arrhizus* (= *R. oryzae*) and *Stemphyllium botryosum* (Camili and Benato, 2005; Sawant *et al.*, 2008; Sholberg *et al.*, 2003; Steel *et al.*,

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2007; Visarathanonth *et al.*, 1988; Xu *et al.*, 1999). Additionally, some yeasts (e.g., *Aureobasidium pullulans* and *Cryptococcus laurentii*) and bacteria (e.g., *Bacillus subtilis*) have occasionally been associated with grape rot in California (Morgan and Michailides, 2004).

Insect damage
Several pests, insect and acari, can severely injure grapes in the vineyard, and their presence and the damage can reduce the quality and acceptability of grapes. Among other pests, grape berry moths (*Lobesia botrana*), mealybugs (*Pseudococcus maritimus*, *P. viburni*, *P. longispinus*, *Planococcus ficus*), western flower thrips (*Frankliniella occidentalis*), vinegar flies (*Drosophila* spp.) and yellow jackets (V*espula* spp.) often injure grapes, facilitating the dissemination and penetration of fungal pathogens. The possible dissemination of some insects and acari on grapes has forced the introduction of specific quarantine treatments to lower the risk of introduction and establishment of new pests in some countries.

9.5.2 Abiotic agents

Abiotic agents can cause considerable deterioration of grape quality and trade value. Therefore, farmers need to be aware of the main abiotic factors in order to preventively control them. The most frequent and important abiotic factors are discussed in this section.

Bleaching
Bleaching caused by SO_2 is characterized by partial or total discoloration of the berry, affecting the anthocyanins and chlorophyll. Bleaching usually starts at the pedicel end because of injuries and weak insertion that allows the penetration of SO_2 inside the berry base. Often, this syndrome is known as ‘sunken’. Experiments done under controlled SO_2 concentrations classified cultivars’ susceptibility to SO_2 as very susceptible (‘Ribier’, ‘Hongbaoshi’ and ‘Red Globe’), moderately susceptible (‘Niunai’), susceptible (‘Kyoho’ and ‘Muscat Hamburg’) and minimally susceptible (‘Longyan’ and ‘Black Autumn’) (Gao *et al.*, 2003). The SO_2-sensitive cultivar ‘Red Globe’ has a loose epicuticular wax structure and a low concentration of superoxide dismutase compared to the minimally susceptible cultivar ‘Longyan’ (Zhang *et al.*, 2003). (See Plate XVI in the colour section between pages 274 and 275.)

Dehydration
Dehydration is a physical process where vapor moves from a high water potential stage to a low water potential stage (water pressure deficit, WPD, condition). Along the postharvest handling chain of grapes, a WPD is produced between the cluster and the atmosphere, which favors water loss. Threshold values of water loss of 4% for ‘Red Globe’, 3.6% for ‘Thompson Seedless’ and 3.3% for ‘Flame Seedless’ have caused rachis browning symptoms under controlled conditions

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(Crisosto *et al.*, 2001). At harvest time, high temperature and low humidity are the main physical factors that promote WPD; however, when the fruit is packed into polyethylene bags, the humidity increases and WPD is reduced; and fruit temperature remains a critical factor. During storage, the time it takes for the cluster to achieve the chamber temperature should be considered as a critical factor to reduce WPD; therefore, forced air cooling has become a required practice in the table grape industry.

The water loss rates of 'Red Globe' clusters following harvest in a commercial grape operation were 1.8% per day during harvest and transport to packaging, 1.33% per day during packaging, 1.09% per day during the wait for forced air cooling, 0.99% per day during forced air cooling and 0.0054% per day during storage at 0 °C (Zoffoli, 2008).

Increasing the humidity inside the box using a restricted ventilation cluster bag and/or box liner has been beneficial for maintaining cluster freshness. 'Red Globe' clusters packed in a box liner with 2.0% ventilation area (VA) lost 1.7 times more weight than those packed in a box liner with 0.3% VA after 60 days storage at 0 °C. 'Red Globe' cluster quality was characterized by shoulder and central rachis thickness lower than 3 mm and 2.5 mm, respectively, at harvest. The clusters had poor rachis quality after 60 days at 0 °C when packed in a 2% polyethylene bag (Zoffoli, 2008).

Hairline cracks

Hairline cracks are an expression of phytotoxicity due to overexposure to sulfur dioxide (SO_2) characterized by the development of small, fine, longitudinal, linear cracks, almost undetectable to the naked eye (Fig. 9.5a). Juice exudation from the split zone makes the berry skins wet and sticky. The incidence of hairlines increases when the concentration and time product (CT) of SO_2 exceeds 3 mL L^{-1} h^{-1}. No hairline is observed when the CT is below 0.8 mL L^{-1} h^{-1}. Difference among orchards has been reported (Zoffoli *et al.*, 2008) and overuse of gibberellic acid (GA) and forchlorfenuron (CPPU), for berry growing explains the susceptibility (Zoffoli *et al.*, 2009a). Therefore, to reduce this disorder it is essential to use a minimal dose of SO_2 that allows adequate decay protection without reducing berry quality (Zoffoli *et al.*, 2008).

Shatter

Shatter (losing berries) is a physical condition representing the proportion of berries that have separated from the cap stem. It may be initiated by an abscission layer at the insertion of the berry to the pedicel during ripening, but symptoms appear at harvest and continue to occur in stored grapes until final consumption. However, in 'Autumn Black' clusters, shatter develops by separation of the berries with their pedicels. Shatter increases as grapes mature, and usually the severity is high in seedless cultivars (e.g., 'Flame Seedless' and 'Thompson Seedless') and low in seeded cultivars (e.g., 'Red Globe'). Therefore, shatter severity varies from season to season, among table grape cultivars and among vineyards, according to harvest time and storage conditions. Table grape management can affect shatter

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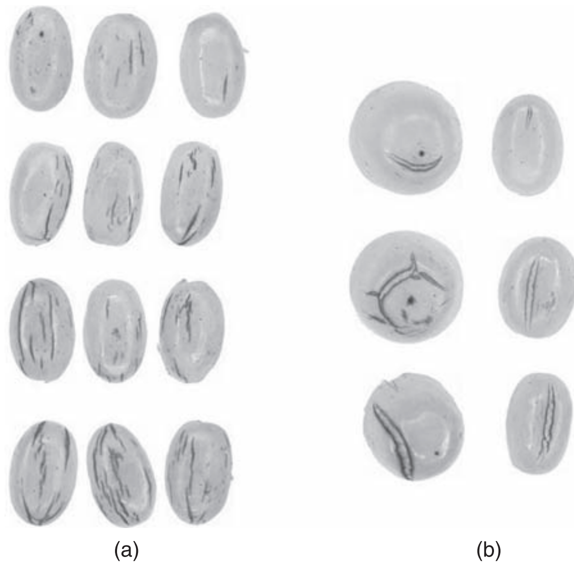

Fig. 9.5 (a) hairline cracks; (b) berry splitting symptoms. Data from Zoffoli *et al.*, 2008.

considerably. For instance, shatter increases with gibberellic acid and after forchlorfenuron applications for berry enlargement. Both growth regulators promote pedicel thickness (Zoffoli *et al.*, 2009a). A positive correlation between pedicel thickness and peroxidase activity, stimulated by post-bloom applications of gibberellic acid to vines, was found (Pérez and Gómez, 1998).

Similarly, shatter can considerably increase under rough handling at harvest and packing. Shatter tolerance has been established in some countries. For instance, a maximum of 3% shatter at harvest is currently accepted for high-quality grapes. Another type of shatter is humid shatter, where berries separate, leaving part of the vascular bundle with the pedicel. This symptom often occurs in 'Thompson Seedless' and is associated with rough handling.

Skin and flesh browning

Berry browning is a physiological disorder, primarily of Muscat-type cultivars with high polyphenol concentrations, such as 'Italia', 'Regal Seedless', 'Victoria', 'Princess' and 'Majestic'. Symptoms are external (skin) and internal (flesh) brown discolorations caused by polyphenol oxidation reactions in the presence of oxygen and polyphenol oxidase in damaged tissues. Skin browning is associated with physical, biological or chemical damage. For instance, rough handling of the grapes during harvest, packaging or transport often induces skin browning. The incidence of skin browning is low at harvest but increases after cool storage, particularly in fruit over-exposed to sun. Skin browning varies from year to year and among orchards. Research performed on the 'Princess' table grape cultivar

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has demonstrated that the incidence of skin browning increases when the grapes are harvested with TSS ≥18% or when the TA is ≤ 0.6% (Vial *et al.*, 2005).

Flesh browning symptoms can affect the entire berry and can be attributed to methyl bromide phytotoxicity (Auda *et al.*, 1977; Leesch *et al.*, 2008). Methyl bromide-treated berries have a significantly lower concentration of the natural antioxidant glutathione (Liyanage *et al.*, 1993). Other flesh browning symptoms can be restricted to the vascular bundles or to the endocarp at the seed or rudimentary seed area (e.g., in 'Thompson Seedless'). In some very susceptible table grape cultivars, e.g. 'Italia', it is postulated that the flesh browning disorder is associated with cell membrane damage induced by chilling injury.

Freezing damage is visible as external browning and a milky color in the berry. The rachis and laterals of the cluster are also affected by freezing temperatures, with similar browning symptoms of water loss. Other external and internal browning symptoms can be caused by abiotic and biotic factors, such as the reddish ring spot at the touch point on the berry surface produced by thrips-feeding activity (Roditakis and Roditakis, 2007; Fourie, 2009). (See Plate XVII.)

Splitting

Fruit splitting is a common disorder in grapes, consisting of circumferential and longitudinal injuries, or both, on the grape berry surface (Fig. 9.5b). For instance, in 'Thompson Seedless' table grapes, circumferential ring fractures usually appear around the pedicel, and longitudinal fractures appear down the sides of over-mature berries. Splitting develops during cell enlargement, coinciding with a high internal hydrostatic pressure. It has been demonstrated that turgor pressures of 15 and 40 atm are required for splitting in susceptible and resistant grape cultivars, respectively (Considine and Kriedemann, 1972). There is evidence that the skin of the grape is reinforced in the region of the lenticels. The split is thought to start from the less viscoelastic tissue surrounding the lenticel (Considine, 1982; Considine and Brown, 1981). Splitting can be induced by irrigation or rain, and it can also occur during storage (Nelson, 1985).

Waterberry

Waterberry is also known as 'bunch stem necrosis' '*palo negro*', 'shanking', '*stiellahme*' and '*dessechement ed al rafle*'. It is characterized by watery, soft, flabby berries that become opaque and lighter in color than normal berries. Waterberry appears during ripening, resulting from necrosis of the phloem in cluster stems and cap stems. Therefore, the flow of metabolites into the berries is interrupted, and the berries remain acidic with low TSS. Waterberry is associated with high total nitrogen and high ammonium levels in the stem tissues produced by lack of ammonium assimilation into proteins (Christensen and Boggero, 1985; Ruiz and Moyano, 1998; Silva *et al.*, 1986). It is favored by high nitrogen fertilization, canopy shading and cool weather conditions during fruit ripening. It can be prevented by reducing nitrogen fertilization and thinning shoots, particularly during ripening. It is especially problematic in the cultivars 'Thompson Seedless', 'Flame Seedless', 'Crimson Seedless', 'Calmeria' and 'Queen';

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however, this disorder also affects wine cultivars (Ureta *et al.*, 1981). Similarly, the development of soft berries with a transparent appearance has also been attributed to high concentrations of nitrogen, arginine and putrescine in the berries (Ruiz *et al.*, 2004).

9.6 Postharvest handling and packaging

9.6.1 Harvest operation

Table grapes are harvested when the grapes reach the optimum acceptability for the consumer, determined mainly by the sugar content (TSS 15 to 17%), titratable acidity (TA) and TSS:TA ratio (>20). Sugar content is measured by the TSS concentration using a refractometer, and the TA is measured by titration with 0.1 N sodium hydroxide to a phenolphthalein of pH 8.2 endpoint. A minimum maturity standard has been adopted by several countries to assure pleasant grapes at the consumer level. Although the critical value varies among countries, a TSS concentration of 16% has been adopted for most table grape cultivars; however, a 15% TSS concentration is considered acceptable in low acid cultivars such as ‘Red Globe’ and ‘Ribier’. In geographical areas where the degradation of acids occurs, a TSS:TA ratio of 20:1 is used as an index to determine the harvest time in early harvested grapes without decreasing the grape quality perception by consumers (Nelson, 1985).

Detachment of grape clusters from the vines should be performed by trained operators, who carefully select mature grapes and avoid mechanical damage. The grape clusters can be trimmed in the field, introduced into a 60×40×25 cm plastic box, transported and packed in small grower-owned sheds or in a large packinghouse with cooling facilities. Clusters should be packed within the first 6 h after harvest.

9.6.2 Packaging operation

There are two possibilities: field packaging and in-house packaging. Field packaging is a harvest operation where grapes are picked, sorted and packed directly into the shipping box. This packaging system allows transportation in a more protected manner and reduces water loss and bruising. In this process, pickers and packers work together, trimming and packing the clusters until finishing the box. The empty and filled boxes are left on the ground and other workers transport them to the shed area where the boxes await transport to the cooling facility. Otherwise, ‘avenue packing’ is an alternative to field packing in which clusters are trimmed and packed in different locations. The clusters are harvested, trimmed, cleaned and put into the field lug. Other workers transport the clusters to a selection and packaging site where clusters are packaged into shipping boxes.

In-house packaging is done in relatively large houses, often under controlled temperature conditions where plastic boxes filled with clusters are placed onto a

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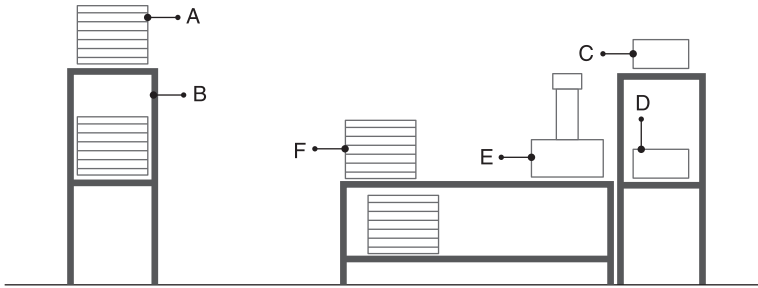

Fig. 9.6 Scheme of working table in packing line operation for table grapes: (A) empty field lugs; (B) fruit in field lugs with untrimmed table grapes; (C) empty shipping boxes; (D) packed boxes; (E) scale; (F) lug for packaging materials (bags, papers, generator pads).

packing belt from which workers start to prepare the clusters. Workers are located at a 'working table' (Fig. 9.6) where the clusters are selected, trimmed and transferred into the cleaned lug. Berries left from the cleaning and trimming operations are collected in individual containers located further down the working table or on a belt-conveyer that moves the dirty materials out of the area. Small, sharp scissors and a scale are provided at the working table. In the packing section, workers are allocated to a packaging table where they take the lug containing clean selected and trimmed clusters from the conveyer and pack clusters into different shipping boxes, according to cluster shape, berry color and cluster size. In a separate line, located 50 cm over the packing table workstation, a roller conveyer moves empty shipping boxes. Packaging materials, such as polyethylene boxes, bags, cartons, wooden or non-returnable plastic boxes, waxed paper, generator pads and plastic or paper bags, are provided at the packing table workstation.

Shipping boxes are transported on pallet bases that are 120×100 cm or 120×80 cm (Europallet) in size. Therefore, the package sizes should meet the requirement of metric shipping containers. Special arrangement on the pallet must be considered when using 40×30 cm, 50×30 cm or 60×40 cm boxes 10 to 13 cm high. The pallet height cannot be more than 1.8 m, with 72 to 96 boxes per pallet depending on box dimensions (Fig. 9.7).

9.6.3 Labeling

Each packaged box should include the necessary information to make it possible to trace the grapes from the vineyard to the market. Therefore, the producer brand name, geographical location, product name and table grape cultivar (variety) should be identified on each shipping box. The weight in kilograms and date of packaging must be indicated as well. Postharvest treatments, such as the use of SO_2, must be clearly marked on the container to comply with market requirements.

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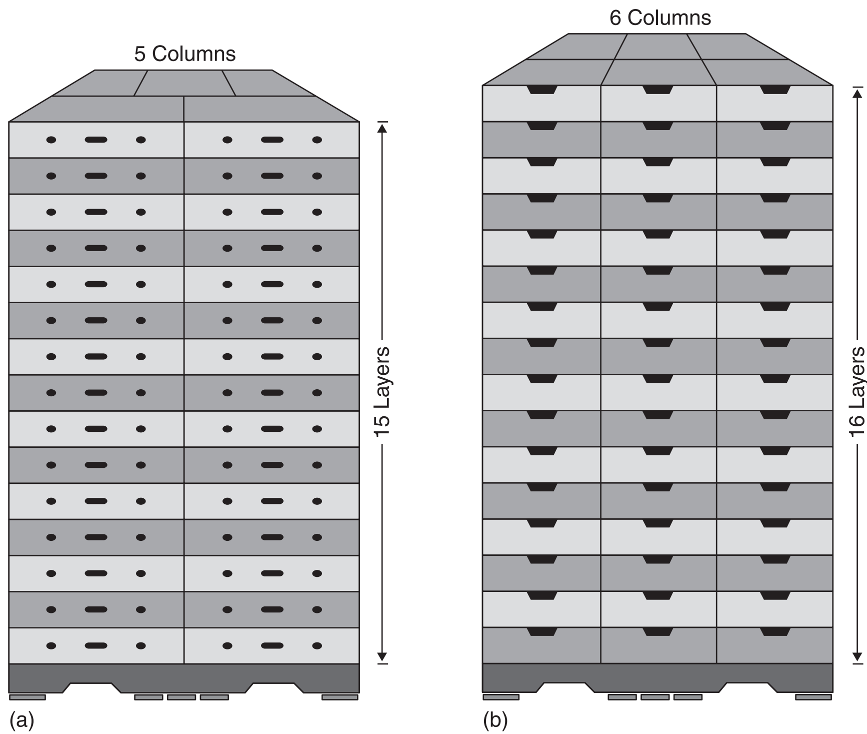

Fig. 9.7 Pallets with two box arrangement types: (a) five columns with 15 layers of 40 cm ×60 cm boxes and (b) six columns with 16 layers of 40 cm×50 cm boxes.

9.6.4 Cooling operation

To avoid condensation on the berry surface during packaging, grapes should not be cooled down to 0 °C immediately after harvest, and trimmed grape clusters must be stored and packed in holding chambers at 15 °C and 90% relative humidity (RH), provided by evaporative cooling systems.

Packed fruit should be stacked for cooling within 6 h after harvest. Forced air cooling, which delivers cool air directly to the fruit by establishing a pressure gradient across the lugs in the pallet, removes the latent heat of the grapes faster than any other cooling system, reducing water vapor deficit and the respiration rate of the grapes and rapidly arresting the development of decay fungi. The speed at which the forced air cooling cools down the grapes from field temperature depends on the volume of air passing through the fruit and on the mass of grapes and the field temperature of the grapes. However, as the air volume increases, the required static pressure greatly increases, raising the energy consumption of the fan. Generally, the system should be designed to deliver 1 to 2 cfm lb^{-1} (0.001 to 0.002 m^3 sec^{-1} kg^{-1}) of packaged grapes (Nelson, 1985) (Fig. 9.8).

Air flowing through packaged grapes meets some resistance. The total resistance depends on the number of packages in line across a stack and the

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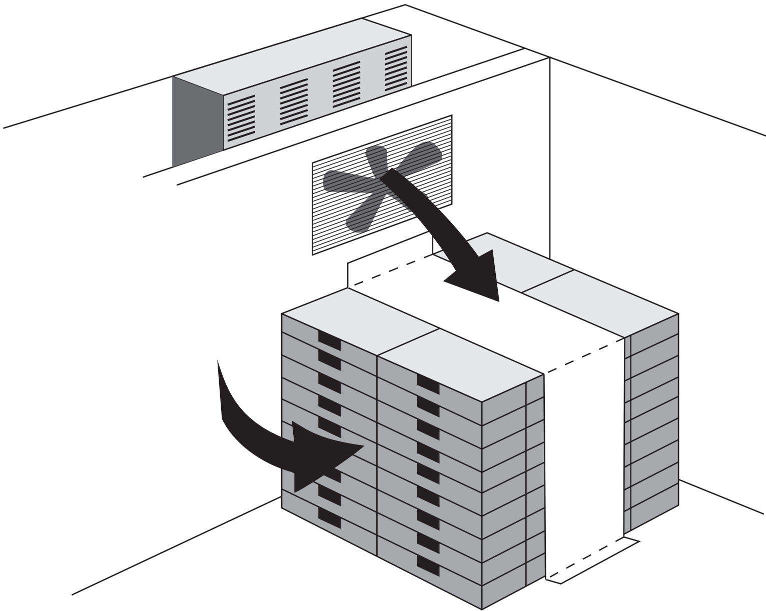

Fig. 9.8 Forced air cooling.

packaging materials used. The bag ventilation area of the box and the use of wax to cover the inside of the box are the main factors that affect the flow of cooling air through packaged grapes. Vented box liners increase the cooling time by a factor of three or four as compared to no liners. Shipping containers including paper in the four sides of the box increase the 7/8 cooling time from 3 to 12 h, when a box liner with 0.3% vent area (VA) is used. The airflow resistance ('static head') is measured as millimeters of water, and the difference in pressure between the outer face of the stack (higher pressure) and the inner face (downstream, where the air leaves) is determined. Any air leakage in the pallet stacking reduces the efficacy of forced air cooling.

A total VA of at least 4% for the vented face has been a general recommendation for the shipping box. However, when grapes are densely packed and a polyethylene bag is included, the vent should be located along the top edge of the vented face. Elongated vents are preferable to round holes.

Conduction cooling rather than convection cooling, by incorporation of a polyethylene bag, promotes water condensation inside the box liner walls; a difference of 4 °C can be found between outer and inner faces of the pallet. Changing the pressure gradient across the pallet reduces the temperature difference but increases the risk of high temperatures in the middle of the pallet; therefore, the viability of this operation should be evaluated before use.

Fruits stacked on a pallet are stored in a cold room, in order to homogenize the fruit temperature before loading them into the container or into the vessel. During

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temperature homogenization, the air speed is set at 1 to 1.5 m s^{-1} compared with an air speed of 0.1 to 0.2 m s^{-1} during the holding period. A period of 3 to 4 days is required for pulp temperature homogenization; the length of this period depends on the fruit temperature and the amount of stacked fruit in relation to the total heat removal capacity of the cold room.

9.7 Temperature management

Recommended pulp temperatures for storage of grapes are −0.5 °C to 0 °C, with 95% RH and an airflow of 20 to 40 cfm t^{-1}. The storage room should be operated between −1 and 0°C, since berries freeze near −2 °C and the rachis freezes at −1 °C.

Forced air cooling reduces the fruit temperature to between 0 to 4 °C within less than 12 h. This operation is usually done with 32 000 kg of packed grapes starting with a 25 to 30 °C pulp temperature.

9.8 Sulfur dioxide treatments

Sulfur dioxide (SO_2) fumigation treatments and/or SO_2 generator pads inside grape boxes have been used for many years as methods of controlling decay caused by *B. cinerea* in stored grapes (Harvey and Uota, 1978; Nelson and Ahmedullah, 1976; Nelson and Baker, 1963). Currently, the use of SO_2 is a standard sanitation practice to treat grapes for long distance transportation and long cold storage. SO_2 fumigation reduces the surface contamination of grape clusters with conidia of *B. cinerea* and prevents the rapid spread of the mycelium of *B. cinerea* by contact between diseased and healthy grapes. Because of its capacity to inhibit enzyme-catalyzed reactions, SO_2 reduces stem browning, helping to maintain the stem appearance for longer periods of time.

9.8.1 Mode of action

SO_2 does not penetrate the intact berry skin, remaining almost completely on the berry surface. Therefore, it only kills spores and mycelia present on the surface of the berries and is unable to control the fungus inside grapes (Nelson, 1958; Smilanick *et al.*, 1990a). However, SO_2 is efficiently absorbed through berry injuries (e.g., hairline cracks, splitting, non-suberized lenticels), resulting in partial or entire berry bleaching.

The fungal toxicity of the SO_2 treatment is attributed almost entirely to the fact that SO_2 can be absorbed passively through the plasma membrane, causing oxidation reactions that affect different metabolic processes of *B. cinerea* and other fungi. The sensitivity of conidia of *B. cinerea* to SO_2 increases two- to fourfold for every 10 °C increment between 0 and 32 °C, which has been attributed to the effect of temperature on SO_2 absorption (Smilanick *et al.*, 1990b) (Fig. 9.9).

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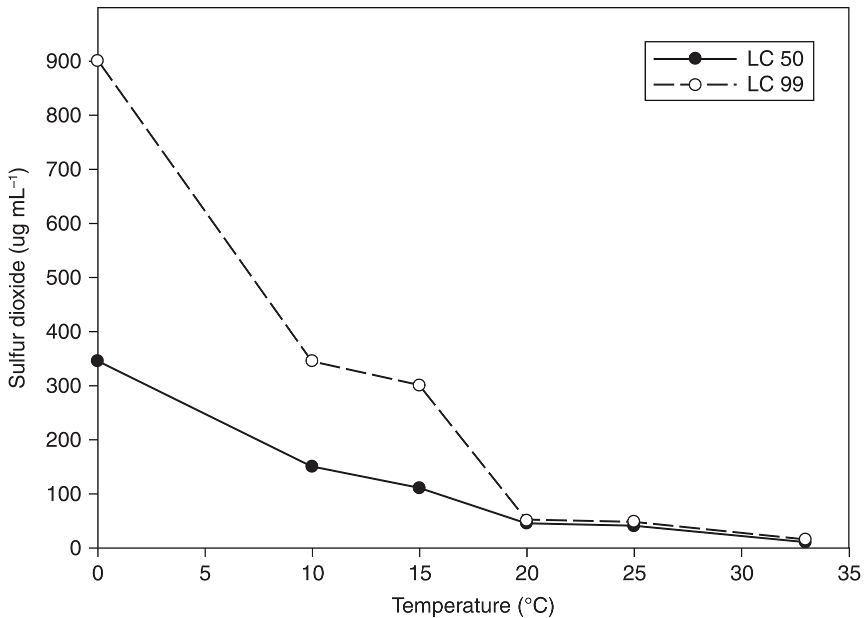

Fig. 9.9 Effect of temperature on the toxicity of sulfur dioxide (SO_2) against *Botrytis cinerea*. Estimated lethal concentrations (LC) to obtain a 50% (LC50) and 99% (LC99) control (data from Smilanick *et al.*, 1990b).

9.8.2 SO_2 dosages

The amount of SO_2 needed to kill conidia and inactivate exposed mycelia of *B. cinerea* at a given temperature is dependent on the SO_2 concentration and the length of the fumigation period. In general, higher SO_2 concentrations are needed to kill conidia than mycelia (Palou *et al.*, 2002a; Smilanick and Henson, 1992).

Formulas for calculating the SO_2 concentration during fumigation are available (Nelson, 1985). However, a concentration time (CT) concept has been developed to calculate the SO_2 exposure needed to arrest grape decay fungi for total use of the SO_2 with minimal SO_2 release into the atmosphere (Smilanick and Henson, 1992). This CT value can be obtained with different combinations of SO_2 concentration and time. For instance, a CT of 100 is near the minimum value (CT 78.3 ± 22.3) needed to kill conidia and inhibit mycelial growth of *B. cinerea* at 0 °C, and it can be obtained using 50 mg L^{-1} for 2 h or 100 mg L^{-1} for 1 h or 200 mg L^{-1} for 0.5 h. For the initial fumigation of grapes after harvest, where the control of spores on the surface of grapes is required, 100 mg L^{-1} – h should be sufficient; for subsequent storage fumigations where control of mycelial growth from latent infections is required, 50 mg L^{-1} – h should be sufficient (Smilanick and Henson, 1992).

It has been demonstrated that a low but constant SO_2 emission rate of 3.6 to 5.5 μmol kg^{-1} h^{-1} is sufficient to arrest the dispersion of gray mold in grapes stored at 0 °C and 95–98% RH (Palou *et al.*, 2002a).

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9.8.3 Pre-packaging SO_2 fumigation

The pre-packaging SO_2 fumigation is commonly done in sealed fumigation chambers, immediately after harvest, using 0.5% SO_2, w/v, for 15 to 20 min at 20–22 °C. To reduce the amount of SO_2 released into the atmosphere, the SO_2 concentration applied must be adjusted, using a dosimeter tube, to 100 mg L^{-1} – h CT value. Different relationships between the initial SO_2 concentration and the CT value will be obtained depending on the amount of fruit and the chamber construction. The grapes are then ventilated before continuing with the packaging process. Alternatively, SO_2 fumigation can be applied using SO_2 guns (e.g., DOSIGAS, Proquivi, Santiago Chile; YTGas, YT Ingeniería Ltda., Viña del Mar, Chile) to deliver an exact amount of SO_2 per box of packaged grapes. A minimum of 60 mL of SO_2 is recommended for 8 kg of fruit. This latter methodology has been useful for grapes packaged in the field, replacing the above-mentioned pre-packaging SO_2 fumigation.

9.8.4 Post-packaging SO_2 fumigation

SO_2 fumigation can be carried out in packaged grapes stored at 0 °C in cold rooms, and it is often performed in conjunction with forced air cooling, using 5000 to 10 000 mg L^{-1} SO_2 for 20 to 30 min (Smilanick *et al.*, 1990b). Forced air cooling ensures a good distribution and penetration of the SO_2 in palletized boxes. Repeated weekly applications with lower SO_2 concentrations (2500 mg L^{-1} SO_2) are needed to prevent a rapid spread of *B. cinerea* by contact between diseased and healthy grapes. SO_2 fumigations at an even lower SO_2 concentration (200 mg L^{-1}), applied three times a week can be successful in cold stored grapes, and the lower concentration reduces the risk of SO_2 phytotoxicity (Marois *et al.*, 1986). Finally, evaluating the CT value at different points in the chamber will ensure that the correct SO_2 concentration is applied.

SO_2 generator pads (e.g., Proteku in Brazil; Fresca, Osku, Proem and Uvas Quality in Chile; Uvasys in South Africa) consist of sodium metabisulfite ($Na_2S_2O_5$) grains enclosed in paper-plastic pockets inside a pad (Nelson and Ahmedullah, 1976; Zoffoli, 2002). The generator pads vary in dimensions (23×33 cm, 20×46 cm, 26×46 cm, 33×46 cm) and can contain 20, 24, 32 or 40 pockets per pad. The $Na_2S_2O_5$, when hydrated by water vapor, continuously emits SO_2, protecting grapes from decay for up to 60 days during cold storage. The rate of emission of SO_2 from a generator pad is proportional to the temperature and humidity inside the box. Currently, one pad containing 8 g of sodium metabisulfite per 8.2 kg box is placed over the grapes in each box, and 0.1 g of sodium metabisulfite is spent per day. These SO_2 generator pads are particularly needed for long ocean shipments, when grapes cannot be subjected to periodic SO_2 fumigations.

SO_2 generator pads made with dual-release SO_2 phases are currently used. The dual-release SO_2 phases are achieved by using small and large $Na_2S_2O_5$ particles, adequate $Na_2S_2O_5$ formulations and a pad made of paper for the fast SO_2 release phase, and one made of polyethylene combined with paper for the

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slow SO_2 release phase. Increasing the proportion of polyethylene in the slow-release phase reduces the amount of sodium metabisulfite, and the same effect is produced by increasing the perforation area of the polyethylene bag (Zoffoli *et al.*, 2005) or enclosing the SO_2 generating pad in a plastic laminated with macro-perforation (Zutahy *et al.*, 2008). Commonly, the SO_2 generator pads contain 1 and 7 g of $Na_2S_2O_5$ in fast-release and slow-release formulations, respectively.

The SO_2 generator pads release SO_2 as a function of temperature and RH (Fig. 9.10). The dynamics of SO_2 emission vary during postharvest storage, achieving a maximum SO_2 concentration after about 2 h at room temperature before pre-cooling; the total fast-release phase is released during the forced air cooling process (Fig. 9.11). Therefore, the SO_2 concentration during cold storage depends on the slow release phase, which is liberated slowly or rapidly depending on temperature variation, RH and condensation inside the box.

The distribution of SO_2 inside packed boxes of grapes is not necessarily uniform; it is generally higher at the top of the box, just below the generator pad (Fig. 9.11). The distribution of the SO_2 also depends on the type of packaging material used as well as the tightness of the pack, the use of pallets and the system of air circulation employed (Harvey and Uota, 1978; Harvey *et al.*, 1988). Because of the uneven distribution of SO_2 inside the packages, the addition of a second SO_2 generator pad, placed at the bottom of the box, has been recommended; however, the risk of phytotoxicity consequently increases considerably. A novel sulfur

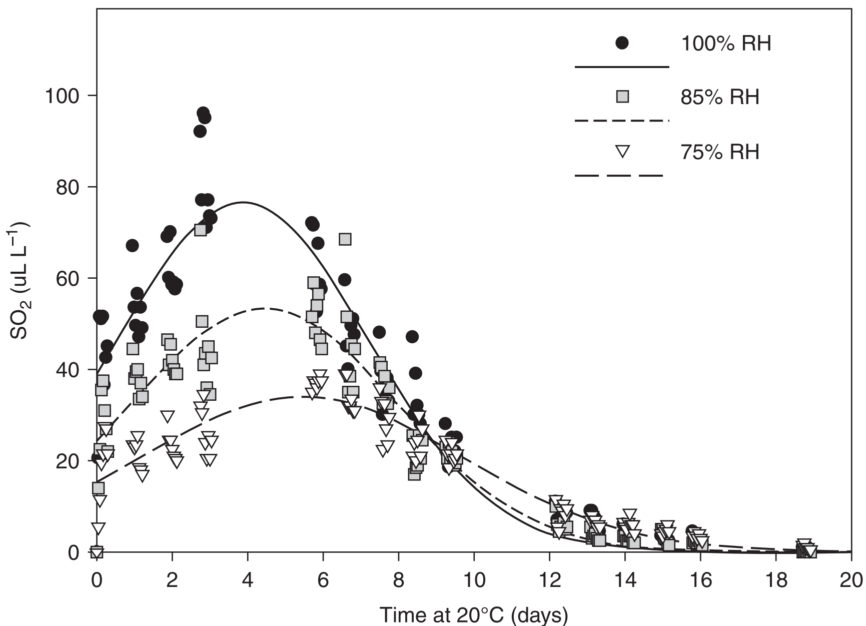

Fig. 9.10 Evolution of SO_2 concentration from generating pad (8 g, sodium metabisulfite) stored at 100%, 85% and 75% relative humidity (RH) and 20°C. Data from Zoffoli, 2008.

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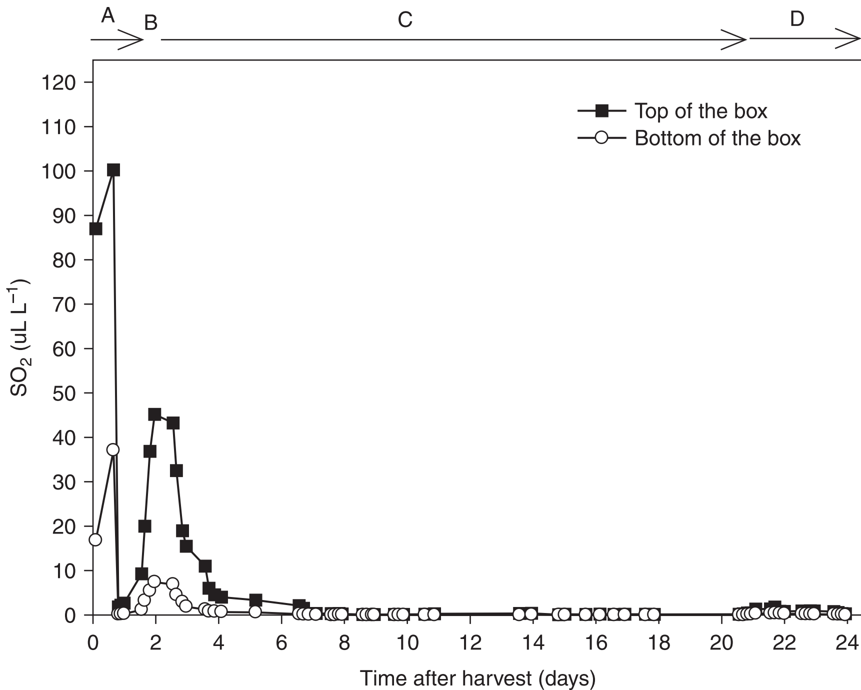

Fig. 9.11 Evolution of SO_2 gas obtained with SO_2 generating pad (Uvasys). SO_2 generating pad was placed at the top of box of 'Thompson Seedless' table grapes. Measurements were made at the top, above the table grapes or at the base of the box, below the table grapes, before cooling at 20°C. Data from Zoffoli *et al*., 2009.

dioxide-releasing perforated plastic liner has been evaluated to improve the uniformity of SO_2 inside the box (Mlikota Gabler *et al*., 2007; Zoffoli *et al*., 2007).

9.8.5 SO_2 tolerance

Because ingestion of SO_2 residues (sulfites) can cause hypersensitive reactions in some people, the Environmental Protection Agency (EPA) established a 10 mg kg^{-1} residue tolerance in the US. At present, the SO_2 used in Europe is considered a food additive, therefore specific labeling is required. In the US, the use of SO_2 is no longer accepted for certified organic grapes, some regulatory agencies do not allow the discharge of SO_2 into the air after fumigation and workers must not be exposed to the gas at levels above 2 mg L^{-1} (Lichter *et al*., 2006).

9.8.6 SO_2 alternatives

Several alternatives to the use of SO_2 have been studied, including the use of acetic acid vapor (Moyls *et al*., 1996; Sholberg *et al*., 1996), chlorine gas (Zoffoli

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et al., 1999) and ethanol (Karabulut et al., 2005). However, these alternatives have not yet been applied commercially (Lichter *et al.*, 2006). Ozone (O_3) has also been evaluated for the same purpose (Palou *et al.*, 2002b; Mlikota Gabler *et al.*, 2010; Sarig *et al.*, 1996). *Muscodor albus* has been formulated for use in a pad or sachet delivery system for biofumigation to control postharvest gray mold through production of lethal alcohol volatiles (Mlikota Gabler *et al.*, 2006). Combinations of 10 or 15% CO_2 with 3, 6 or 12% O_2 have been proven to be effective in controlling *B. cinerea* in late-harvested 'Thompson Seedless' table grapes for up to 90 days at 0 °C (Crisosto *et al.*, 2002).

9.9 Quarantine treatments

Table grapes for the export market must comply with sanitary requirements imposed by the importing countries. For instance, grapes shipped to the US should comply with the rules established by the USDA Animal and Plant Health Inspection Service (USDA-APHIS). According to these rules, quarantine treatments, consisting of methyl bromide fumigation or continuous low temperature treatment, must be applied to grapes imported from any country.

The concentration and time of methyl bromide fumigation depends on the berry temperature. The lower the temperature, the higher the concentration of methyl bromide needed to kill the insects for which the quarantine is imposed. However, it should be considered that the risk of berry phytotoxicity is increased with high methyl bromide concentrations. A summary of the protocol for methyl bromide application is described in USDA-APHIS PPQ (2009), and an example is provided in Table 9.2.

Methyl bromide is currently being restricted because of health, safety and environmental concerns (as it is a stratospheric ozone-depleting substance). Therefore alternatives have been evaluated, but efficacy appears to be variable between insects, among life stages of insects and with regard to the effect on fruit quality. Among laboratory studies ethyl formate appears to be the most promising volatile compound for postharvest insect control on table grapes (Simpson *et al.*, 2007).

Table 9.2 Quarantine treatment of methyl bromide fumigation for table grape entering the US from Chile to mitigate the pest risk of *Brevipalpus chilensis*

Temperature °C	Dosage rate		Minimum concentration readings (g m^{-3})	
	g m^{-3}	Lb 1,000 ft^{-3}	0.5 h	2.5 h
>26.5	24	1.5	10	14
21–26.4	32	2.0	26	19
15.5–20.9	40	2.5	32	24
10.0–15.4	48	3.0	38	29
4.5–9.9	64	4.0	48	38

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9.10 Transport

The commercialization of table grapes requires the selection of a transport system that allows the maintenance of a uniform fruit temperature, optimum air circulation and compatibility between fruit species. Transportation times for countries located 30 to 40 days away from the markets are critical because most of the postharvest life of the grape will be spent in a refrigerated marine container or inside the cold chamber of the vessel.

9.10.1 Marine containers

Marine containers are available in capacities of 28, 59 and 68 m^3. They have independent refrigerated units, powered by 220- or 440-volt three-phase electricity that allows for direct plugging in to the electric power system on the vessel or at port. A temperature of −0.5 °C should be specified in the container thermostat for grapes. Containers are designed to deliver and maintain the storage temperature, and they cannot reduce the grape temperature during transport.

Because of low grape respiration rates and low ethylene sensitivity, marine containers loaded with grapes should be set without air exchange. It is important to consider that the SO_2 produced by the SO_2 generating pads accumulates, so grapes must not be loaded along with fruits or vegetables sensitive to SO_2 damage, such as apples, pears, plums, peaches or nectarines. Otherwise, washing with alkaline solution is required in order to avoid corrosion inside the container.

The marine containers should be cooled down to −0.5 °C, which is the desired transport temperature, while they are connected directly to the electric system of the dock. If the marine containers are open at the dock in a humid environment, the marine containers should be cooled to the dew point temperature of the outside air in order to avoid condensation inside the container (Thompson *et al.*, 2000). Dew point values in relation to temperature and RH are given in Fig. 9.12.

A uniform temperature inside the container can be obtained by following proper loading practices (Thompson *et al.*, 2000). In contrast to the horizontal air flow of cold chambers and forced air cooling, refrigerated containers are equipped with a bottom air delivery system. Air from the refrigeration unit flows from the floor through the packages vertically and returns horizontally across the top of the load and back to the refrigeration unit to complete the air cycle. To allow vertical airflow from the floor to the pallet load, pallet containers and inner packaging should have sufficient venting and air space, and the floor should be completely covered by the produce or by a solid material. If the produce is palletized, the pallet opening for forklifts should also be covered to block air from traveling horizontally. The open floor between pallets should also be covered. A description of loading systems is provided in Fig. 9.13. Temperature recorders should be installed in order to register the supply and return air temperatures.

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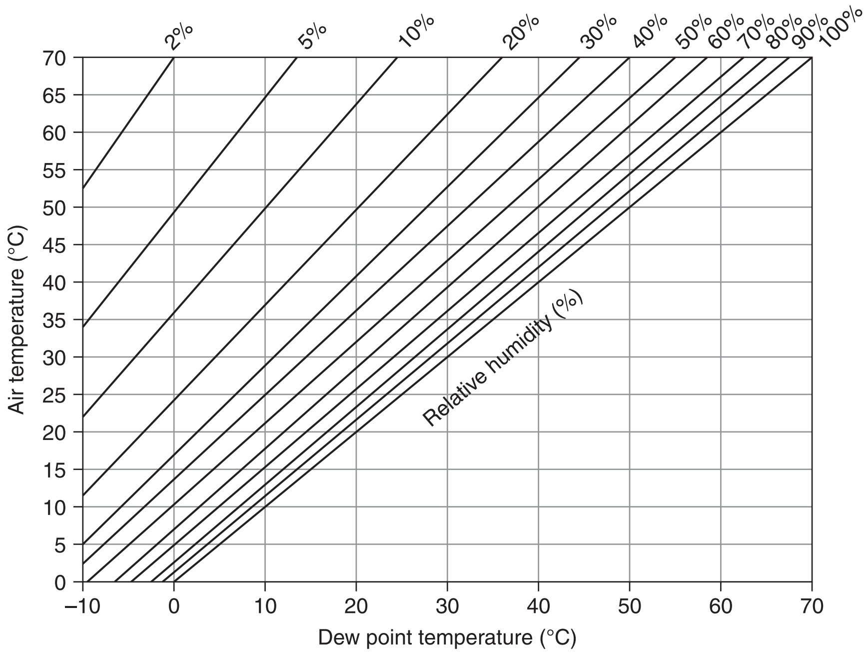

Fig. 9.12 Dew point temperature related to relative humidity and air temperature.

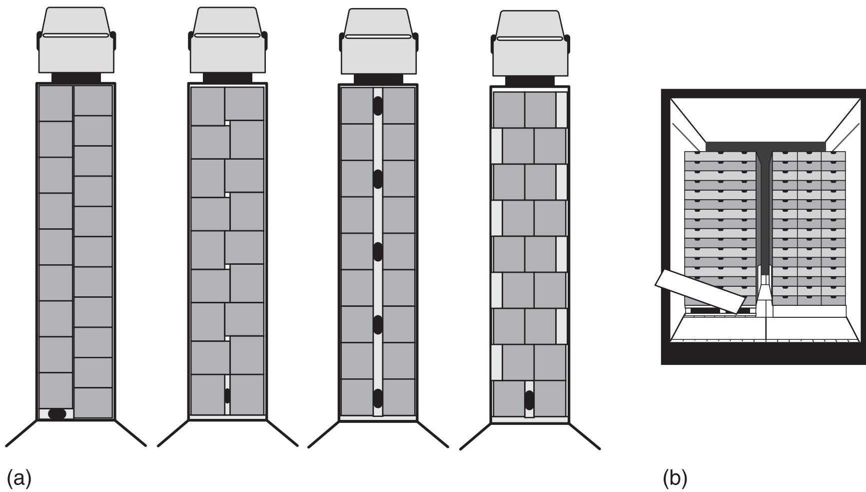

Fig. 9.13 (a) Pallet distribution inside the container; (b) view of pallet and floor covering to improve vertical air circulation. Data from Thompson *et al.*, 2000.

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9.11 Processing

Grapes are often produced for fresh consumption, such as table grapes, but they are also sold as the following products: grape juice, partially fermented grape juice ('chicha' in some Latin-American countries), wine, alcoholic beverages (e.g., brandy, cognac, grappa, jerez, oporto, pisco and singani), wine vinegar, grape jam, grape preserves and raisins. Additionally, grapes can be used to produce grape seed oil used for cooking, salad dressings or cosmetic products (e.g., body creams and lip balm). Although specific grape cultivars are used to elaborate each product, table grape cultivars are often produced both for fresh consumption and for drying as raisins. In this section, general information regarding raisin production is presented.

9.11.1 Raisins

Since ancient times, raisins have been produced from a different type of table grape cultivars, such as *V. vinifera*, from which raisins acquire their characteristic flavor, aroma, color, shape and size. Raisin production is an industry of 700 000 tons worldwide. The largest raisin-producing countries, which account for over 80% of the global raisin production, are Turkey and the United States, which annually produce 230 000 tons and 250 000 tons, respectively. Raisins are also produced in Afghanistan, Argentina, Australia, Chile, Greece, India, Iran, Mexico, South Africa, Spain and other countries where the climate for raisin production is ideal with very dry, warm summers and mild winters (USDA, 2008).

Raisins are a good source of folic acid, pantothenic acid, vitamin B6 and other vitamins that are essential for human nutrition. They are also an important source of calcium, magnesium, phosphorus, iron, copper and zinc. Raisins do not have any fat, which is considered an advantage for human nutrition (Bongers *et al.*, 1991). They are a naturally stable food and are resistant to spoilage because of their low moisture content, high amount of soluble solids and low pH.

Grape cultivars and type of raisins

Four types of raisins are demanded internationally: dark-skinned raisins (sun-dried raisins), golden raisins (heat-dried raisins), Corinth raisins (small, dark raisins primarily from 'Black Corinth' grapes) and snack raisins (large raisins).

Raisins are produced primarily from the following types of grapes: 'Thompson Seedless', 'Black Corinth', 'Fiesta', 'Flame Seedless' and 'Muscat'. 'Thompson Seedless' is one of the most important grape cultivars for the production of raisins because of its oval and elongated shape, early ripening and the grapes' facility to remain separated from each other after drying. However, in a test of several cultivars, 'Thompson Seedless' consistently dried the slowest (Ramming, 2009). Other cultivars, such as 'Black Corinth' which originated from Greece, yield smaller raisins than the 'Thompson Seedless' cultivars. Raisins produced from 'Black Corinth' cultivars are valued by the pastry industry because of their size,

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spherical shape, reddish to black color, thin skin and tendency to be seedless. They perform well because of their early ripening, quick drying and high production.

Muscat grape cultivars, such as the 'Muscat of Alexandria' cultivar, are another important source for raisin production because they are large, juicy and contain few seeds. They are also dull green in color and have a sweet and attractive muscat flavor. However, the seeds must be removed before drying.

Raisin production process

The overall raisin production process includes the following: grape harvesting, drying, processing and packaging.

Grape harvesting

Grapes are hand picked or machine harvested at the maximum concentration of sugar that is evaluated by the TSS content (19%–24%) (Christensen *et al.*, 1995). Mechanized fruit harvest requires a special trellising system that facilitates vine pruning, vine harvesting and cane cutting before the grapes are harvested to aid in fruit removal and to minimize mechanical damage.

Grape drying

Raisins can be produced using natural and artificial drying methods. Natural methods include sun-dried and dried-on-vine, whereas artificial methods include the use of heated air dryers. Natural methods are usually preferred because of the costs. During raisin drying, moisture content is reduced from approximately 75% to below 15%, yielding approximately 1 kg of raisins out of 4 kg of grapes. The final grape color change to brown or dark brown depends on the grape cultivar and the drying method, and the sensory quality is commonly affected by the drying process used (Thompson, 2000).

Sun-dried

Sun-dried grapes are produced by placing grape clusters on 80 cm by 90 cm papers or polyethylene trays that are either short (2 m to 6 m) or long (greater than 6 m). The trays are laid out on concrete floors next to the vineyards or on leveled ground between the vine rows or next to the vineyards, for two to four weeks depending on weather conditions. When the moisture content is reduced to approximately 15%, the individual short paper trays are rolled up with the raisins to form packages, or the raisins are swept into boxes or bins and transported to a processing plant. The disadvantage of the short trays is that they cannot be easily rolled up like a cigarette to protect the raisins against over-drying, caramelization and rain.

Long trays usually require turning and pickup machinery that reduces cost and eliminates all manual handling of trays after picking. Pickup machines can be self-propelled or tractor-pulled. The raisins are placed in bins behind the pickup unit or across the row to a separate bin on a tractor-pulled trailer (Christensen and Peacock, 2000).

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Dried-on-vine

The dried-on-vine method of raisin production often uses mechanical harvesters, and this method is accomplished by maintaining the attachment of grape clusters to the vines that have been trained to allow the clusters maximal sun exposure. With this method, 50% of the fruit near the leaf area is removed by hand pruning the canes six weeks before harvest. During the cane cutting, clusters are dipped in a 0.5% ethyl oleate and 0.6% potassium carbonate solution to increase the drying rate and to achieve the desired light-gold fruit color in the 'Thompson Seedless' raisins (Dincer, 1996; Uhlig *et al.*, 1996). The dried-on-vine method reduces the risk of rain damage, and it is less labor intensive than raisin production by sun drying.

Hot-air drying

In the hot-air drying method, grapes are hand-harvested and transported to a drying facility that has a concrete tunnel with a fan and propane burner mounted above the drying chamber to provide hot air flow that is between 65°C and 70°C. To facilitate water loss, grapes are dipped for 8 to 15 seconds in a hot solution at 82°C that contains 0.2%–0.5% sodium hydroxide and then are rinsed with cold water. The grapes are then spread on drying trays and treated for 5 to 8 hours with SO_2 at a concentration of 2 kilograms to 4 kilograms per ton of grapes. This drying method has the advantage of ensuring a uniform supply of golden raisins, but the relatively high cost limits its use. Other pretreatment techniques, such as the use of a microwave or a pulsed electric field, are being evaluated (Dev *et al.*, 2008).

A high correlation exists between the residual polyphenol oxidase (PPO) activity and the darkness of the raisins, known as the Hunterlab L value, after drying the raisins at 50°C. Addition of SO_2 reduces the PPO activity and enhances the production of light-colored raisins. Further, pretreatment of the grapes in 93°C water with a 2 minute dip produced similar results (Aguilera *et al.*, 1987).

For drying, the grapes are loaded onto 90 cm by 180 cm trays made of wood or plywood. The trays are supported in wheeled trucks that hold 25 to 26 trays each. Truck holders move through the tunnel in the opposite direction to the hot air, which allows the hottest product to be in contact with the highest temperature of air. Air temperature is kept at 65–70°C, and it has to be adjusted depending on the amount of fruit in the tunnel to avoid sugar caramelization and off-flavor development (Thompson, 2000).

Raisin processing

At the processing plant, raisins are passed over wire screens that are shaken to remove dirt and debris. Raisins can be stored for later processing at this time, and in this case, methyl bromide or phosphine fumigant is used to avoid insect infestations during storage.

Otherwise, raisins are emptied onto a conveyer line where the residual debris is removed by passing the raisins over a fine mesh screen with forced air blowing

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on them. The raisins are then shaken to be separated from bunches followed by the removal of cap stems, either mechanically using two rotating, conical surfaces or manually. When raisins are produced from seeded grape cultivars, the seeds are mechanically removed at this stage. Finally, raisins are sorted according to their size by passing them through a series of mesh screens.

Raisins are then placed into packages ranging in size from small, one-half ounce cardboard containers for individual consumption to large, 10 kg or 500 kg containers for industrial use. Raisins are stored and transported under cold conditions (10–15°C) with 50–60% RH. To maintain the raisin quality, a low oxygen atmosphere of 1% is recommended (Guadagni *et al.*, 1978).

9.12 Conclusions

Table grapes are grown in vast areas that include Mediterranean, tropical and subtropical regions. Most of the varieties are sold for fresh consumption and as raisins. Grape is a non-climacteric fruit with a relatively low respiration rate. Main changes in berry composition and softening occur after veraison, promoted by abscisic acid synergistically with ethylene. Decay (biotic) and dehydration (abiotic) are the main deterioration factors of table grape during storage at 0°C. Fungicide application integrated with cultural management of the vine during preharvest reduces the risk of decay, and in combination with 0°C and 90–95% relative humidity maintains the freshness of the rachis during storage. The use of in-package SO_2 release or periodic SO_2 fumigation during storage is required to protect the grape from decay during storage and transport, making the table grape industry highly dependent on this compound.

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(a)

(b)

Plate XV (Chapter 8) (a) Mature green and ripe golden apple fruits without sooty mould on fruit skin; (b) mature green golden apple fruits with sooty mould covering extensive areas on fruit skin.

(a)

(b)

(c)

Plate XVI (Chapter 9) Berry bleaching symptoms produced by SO_2. SO_2 penetrates around the insertion of berry pedicel in (a) Thompson Seedless; (b) Red Globe berries. SO_2 penetrates through cracks on berries in (c) Red Globe.

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(a)

(b)

(c)

(d)

Plate XVII (Chapter 9) (a) Internal browning of Thompson Seedless; (b) and (c) cold damage, berries exhibit light brown discoloration with stem browning; (d) abrasion damage.

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10

Guava (*Psidium guajava* L.)

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Abstract: Guava is a commercial fruit crop in many tropical and sub-tropical countries of the world. The fruit is a rich source of vitamins, minerals, fibre and dietary antioxidants. High perishability and susceptibility to physical damage, chilling injury, diseases and insect-pests are the major postharvest constraints of guava fruit. This chapter reviews the economic importance, postharvest physiology, maturity indices and effects of pre- and postharvest factors on guava fruit quality. Postharvest diseases, disorders and phytosanitary treatments are also reviewed. The chapter then discusses the harvest and postharvest handling procedures and methods of ripening and senescence control. The processing of guava fruit into fresh-cut and other processed products is also described.

Key words: *Psidium guajava*, guava, maturity indices, postharvest quality, storage, processing.

10.1 Introduction

10.1.1 Origin, botany, morphology and structure

Guava (*Psidium guajava* L.) is a member of the *Myrtaceae* family. The genus *Psidium* includes about 150 species, but *Psidium guajava* is the most important fruit of this genus (Pommer and Murakami, 2009). Guava is believed to have originated from an area extending from southern Mexico into or through Central America (Morton, 1987). The Spaniards and Portuguese are considered to be responsible for distribution of guava fruit to other parts of the world. The wide adaptability of the guava tree to various soils and climates may have facilitated its naturalization in tropical and sub-tropical regions worldwide. Botanically, guava fruit is a berry. Fruit are medium to large in size with an average weight of 100–250 g and 5–10 cm in diameter, and have four or five protruding floral remnants (sepals) at the apex (Fig. 10.1). Based on the cultivar, fruit can be spherical, ovoid or pyriform in shape. Fruit surface is rough to smooth, free of

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Fig. 10.1 Guava (*Psidium guajava* L.) fruit and leaves.

pubescence. Skin colour of immature and unripe fruit is mostly dark green which changes to yellowish-green, pale yellow and yellow with red blush on shoulders at ripe stage depending upon the cultivar. Pulp of ripe fruit is soft and juicy and is white, pink or salmon-red (see Plates XVIII and XIX in the colour section between pages 274 and 275). The seed cavity at the centre of fruit may be small to large with many hard to semi-hard seeds. The outer mesocarp of guava fruit is sandy or gritty in texture due to presence of stone cells (78%), which have strongly lignified cell walls, whereas endocarp tissue is rich in parenchyma cells and low in stone cells (Marcelin *et al.*, 1993). Thick pulp, few seeds and stone cells, high sugar concentrations and typical aroma are the desirable fruit characteristics for table purposes.

10.1.2 Worldwide distribution and economic importance

Guava is commercially cultivated in many tropical and sub-tropical countries of the world. India is the largest producer of guava fruit followed by Pakistan, Mexico and Brazil (Singh, 2010 and references therein). Egypt, Thailand, Colombia, Indonesia, Venezuela, Sudan, Bangladesh, Cuba, Vietnam, the US, Malaysia, Puerto Rico and Australia are among the other guava producing countries. A list of some popular guava cultivars grown in different countries is presented in Table 10.1. In response to increasing demand for fresh fruit and processed products, the

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Table 10.1 Major guava cultivars in the producing countries of the world

Country	Cultivar(s)
India	'Allahabad Safeda', 'Lucknow-49' (syn. 'Sardar'), 'Banarsi Surkha', 'Apple Colour', 'Chittidar', 'Nasik', 'Dholka', 'Dharwar', 'Habshi', 'Seedless', 'Red Fleshed', 'Behat Coconut', 'Hisar Safeda'
Pakistan	'Safeda', 'Allahabad', 'Lucknow-49', 'Red Fleshed', 'Seedless', 'Karela', 'Apple Colour'
Mexico	'Media China', 'Regional de Calvillo', 'China', 'La Labor', 'Acaponeta', 'Coyame', 'Kumagai', 'Paluma', 'Rica', 'White Ogawa', 'Red Ogawa'
Brazil	'Paluma', 'Rica', 'Pedro Sato', 'Kumagai', 'Ogawa', 'Sassaoka', 'Yamamoto', 'Século XXI'
Egypt	'Bassateen El Sabahia', 'Bassateen Edfina', 'Allahabad Safeda'
Thailand	'Beaumont', 'Okinawa', 'Glom Sali', 'Glom Toon Klau', 'Khao Boon Soom'
Colombia	'Puerto Rico', 'Rojo Africano', 'Extranjero', 'Trujillo'
Indonesia	'Indonesian Seedless', 'Indonesian White'
Malaysia	'Kampuchea', 'Jambu Kapri', 'Hong Kong Pink', 'Jambu Biji', 'Putih', 'Maha 65', 'Bentong Seedless', 'Taiwan Pear', 'Vietnamese'
Bangladesh	'Swarupkathi', 'Mukundapuri', 'Kanchannagar', 'Kazi'
Australia	'Allahabad Safeda', 'Lucknow-49', 'Indonesian Seedless', 'Beaumont', 'Ka Hua Kula', 'GA-11'
USA (Hawaii)	'Beaumont', 'Ka Hua Kula', 'Hong Kong Pink', 'Indonesian Seedless'
USA (Mainland)	'Redland', 'Supreme', 'Red Indian', 'Ruby X', 'Miami Red', 'Miami White', 'Blitch', 'Patillo', 'Webber', 'Rolfs', 'Hart', 'Detwiler', 'Turnbull'
South Africa	'Fan Retief', 'Frank Malherbe', 'TS-G2'
Vietnam	'Xa Ly Nghe', 'Ruot Hong Da Lang', 'Xa Ly Don'

Sources: Morton, 1987; Pommer and Murakami, 2009; Singh, 2010

production of guava has considerably increased in the current decade as the new plantations of improved varieties and hybrids are emerging. The increase in area and production of guava could be attributed to the breeding efforts in various countries. The international trade of fresh guavas is currently limited, but the processed products, such as juice, nectar, paste, puree and jam, are becoming increasingly popular in the European and North American markets.

10.1.3 Uses, nutritional value and health benefits

Guava has been used as a food crop and medicinal plant. Guava fruit has a sweet-sour taste combined with a pleasant aroma. It is mainly consumed as fresh or processed into various products like fresh-cut salads, juice, nectar, paste, puree, concentrates, jam, jelly, candy bars, etc. Generally, white-fleshed cultivars are preferred for dessert and red-fleshed for processing. The extracts of roots, bark,

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leaves and fruit have been widely used for traditional medicinal purposes in Central America and Africa against diarrhoea, gastroenteritis and antibacterial colic pathogenic germs of the intestine (Pérez-Gutiérrez *et al.*, 2008). Leaf extracts of guava have been widely researched for their antimicrobial properties and have diverse applications in curing various maladies. The pharmacological and clinical uses of guavas have been comprehensibly reviewed elsewhere (Pérez-Gutiérrez *et al.*, 2008).

Fresh guava fruit is low in calories and rich in several vitamins and minerals. According to the national nutrient database of the United States Department of Agriculture (USDA), the major nutritional components of fresh guava fruit per 100 g are: sugars 8.92 g; vitamin C 228.3 mg; vitamin A 624 IU; vitamin E 0.73 mg; vitamin K 2.6 μg; lycopene 5.2 mg (in red-fleshed cultivars only); potassium 417 mg; phosphorus 40 mg; magnesium 22 mg, and calcium 18 mg (USDA, 2010). It is an excellent source of antioxidants, such as ascorbic acid, carotenoids and phenols (Kondo *et al.*, 2005; Lim *et al.*, 2007), which are known to play an important role in the prevention of chronic and degenerative diseases. Similar to many other fruits, polyphenols contribute significantly to the higher antioxidant capacity of guavas. The presence of a high concentration of dietary fibre (48–49 % on dry matter basis) in the peel and pulp of guava fruit makes it a natural food product that meets requirements for consideration as an antioxidant dietary fibre (Jiménez-Escrig *et al.*, 2001). The distribution of various health-promoting phytochemicals also varies within the fruit and from cultivar to cultivar. Fruit skin is higher in ascorbic acid and phenols than flesh (Bashir and Abu-Goukh, 2003; Kondo *et al.*, 2005; Lim *et al.*, 2007). Generally, white-fleshed cultivars contain higher concentrations of ascorbic acid, phenols and sugars (sucrose, fructose and glucose) than red-fleshed ones (Bashir and Abu-Goukh, 2003; González-Aguilar *et al.*, 2004); seeded cultivars have higher phenols and ascorbic acid than their seedless counterparts (Lim *et al.*, 2007).

10.2 Fruit development and postharvest physiology

10.2.1 Fruit growth, development and maturation

Flowering and fruiting in guava occurs continuously throughout the year under mild subtropical and tropical conditions. In subtropical climates of north India, guava flowers in summer, rainy and winter seasons, and thus produces fruit during rainy, winter and spring seasons, respectively (Rathore, 1976). Guava fruit shows a double sigmoidal growth curve (Rathore, 1976; Mercado-Silva *et al.*, 1998). The growth period can be divided into three distinct phases: (1) rapid phase of growth extends for 45 to 60 days after anthesis; (2) relatively slow lasts for 30 to 60 days during which seeds become fully mature and hard; and (3) exponential phase lasts for 30 to 60 days and ends at fruit maturity (Rathore, 1976). During the last phase of growth, fruit show the highest increase in weight and diameter in addition to other changes such as decrease in hardness, chlorophyll and tannins. Other major biochemical changes during the final phase of growth

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include an increase in soluble solids concentration (SSC), titratable acidity and ascorbic acid (Rathore, 1976; Mercado-Silva *et al.*, 1998; Singh and Jain, 2007). However, the length of each growth phase is strongly influenced by climatic conditions and cultivar type. For example, in Mexico, the number of days required for the 'Media China' cultivar to reach the ripe stage is 130 days during spring–summer and 190 days in autumn–winter season (Mercado-Silva *et al.*, 1998). In north India, the growth of seeded fruit of 'Allahabad Safeda' during 30 and 105 days after pollination was greater than fruit of 'Allahabad Seedless' and it was mainly due to the higher levels of gibberellins in the former due to presence of seeds (Nagar and Rao, 1982). The seeded fruit grew faster and reached their largest diameter on the 120th day after pollination, while the seedless fruit at maturity were less than half the size of the seeded fruit. In general, guava fruit take about 100 to 150 days from full bloom to harvest.

10.2.2 Respiration and ethylene production

Guavas are generally classified as a climacteric fruit (Akamine and Goo, 1979; Brown and Wills, 1983; Mercado-Silva *et al.*, 1998; Singh and Pal, 2008a), but some cultivars are non-climacteric in nature (Azzolini *et al.*, 2005). Respiration rate of fruit is influenced by many factors such as cultivar, season and maturity. For example, white-fleshed cultivars respire more slowly than pink-fleshed ones (Bashir and Abu-Goukh, 2003; Singh and Pal, 2008a). The postharvest climacteric peaks in respiration and ethylene production were observed after 4–5 days in spring–summer fruit compared with 7–8 days in autumn–winter fruit (Mercado-Silva *et al.*, 1998). During fruit ripening, ethylene production and respiration rates of fruit harvested at the full sized, pale green stage were higher than those harvested at small or medium dark green stage (Brown and Wills, 1983). Fruit harvested at advanced maturity reach their respiratory climacteric in 4–6 days accompanied by rapid changes in skin colour and flesh firmness. Like respiration, ethylene production behaviour of guava depends upon the cultivar, harvest maturity and storage conditions. Ethylene production rates increase during fruit ripening and reach a peak that may or may not coincide with the respiratory peak. Guava cultivars such as 'Allahabad Safeda', 'Apple Colour' and 'Hisar Safeda' produce higher amounts of ethylene than 'Lucknow-49' (Mondal *et al.*, 2008; Singh and Pal, 2008a). It is suggested that the lower ethylene rates and higher concentrations of polyamines in 'Lucknow-49' are responsible for its better shelf-life compared to 'Hisar Safeda'. The increase in ethylene has been correlated with increased 1-aminocyclopropane-1-carboxlylic acid (ACC) oxidase activity during fruit ripening indicating ACC oxidase may be a limiting step in ethylene biosynthetic pathway in guava fruit because ACC content increased progressively throughout fruit ripening (Mondal *et al.*, 2008).

Guava fruit respond to the exogenous application of ethylene depending upon fruit maturity and climacteric or non-climacteric nature of the cultivar (Reyes and Paull, 1995; Azzolini *et al.*, 2005). The exogenous application of ethylene, for example, enhanced changes in skin colour and softening in

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immature, green fruit of the 'Beaumont' cultivar, but did not affect the ripening behaviour of quarter-yellow fruit of this cultivar (Reyes and Paull, 1995), while 'Pedro Sato' guavas harvested at a mature, light green stage did not respond to postharvest ethylene treatment (Azzolini *et al.*, 2005). However, postharvest exposure to 1-methylcyclopropene (1-MCP), an ethylene action inhibitor, inhibits ethylene production rate and delays fruit ripening in both climacteric and non-climacteric type cultivars (Azzolini *et al.*, 2005; Bassetto *et al.*, 2005; Singh and Pal, 2008b).

10.2.3 Biochemical changes during fruit ripening

During fruit ripening, chlorophyll content decreases and carotenoid content increases, causing skin colour to change from green to yellow (Jain *et al.*, 2003). The intensity of red blush on fruit shoulders also increases in some cultivars. The flesh colour also changes to creamy white, yellow, pink or salmon red depending on the cultivar. The carotenoids contribute to the flesh colour of guava fruit; the relative amounts of different carotenoids determine the intensity of flesh colour. In general, total carotenoids concentrations increase during fruit ripening (Jain *et al.*, 2003). Lycopene (50 μg/g) is the major carotenoid pigment in red fleshed guavas, in addition to the presence of β-carotene (3.7 μg/g) (Wilberg and Rodriguez-Amaya, 1995; Mercadante *et al.*, 1999). In a Brazilian red guava cultivar 'IAC-4', 16 carotenoids have been identified which include lycopene, β-carotene, phytofluene, γ-carotene, β-cryptoxanthin, rubixanthin, cryptoflavin, lutein, and neochrome (Mercadante *et al.*, 1999).

During ripening, fruit softening in guava is accompanied by significant modifications in cell wall carbohydrates. Total pectin content, generally, increases initially and then declines at the overripe stage. The soluble pectins increase as the fruit ripening progresses. The concentrations of chelator-soluble-polyuronides and -carbohydrates also increase during fruit ripening. The levels of other cell wall carbohydrates such as cellulose, hemicellulose, lignin and starch decrease during fruit ripening (Jain *et al.*, 2003). The rate of fruit softening may vary from cultivar to cultivar, but the extent of pectin solubilization was comparable in two guava cultivars: 'Beaumont', a rapid-softening cultivar, and 'Kampuchea', a slow-softening cultivar. 'Beaumont' guava took about 1.5 days to reach 50% of initial firmness at harvest, while 'Kampuchea' took about 24 days (Ali *et al.*, 2004). The collective action of cell wall hydrolyzing enzymes, polygalacturonase (PG), pectin methylesterase (PME), β-galactosidase, (1→4)-β-glucanase and cellulase, causes significant textural changes in guava fruit. PG activity increases progressively during fruit ripening in guavas, while PME increases initially and then declines (Abu-Goukh and Bashir, 2003; Jain *et al.*, 2003). A significant increase in activities of other enzymes like β-galactosidase, (1→4)-β-glucanase, and cellulase also contributes to the cell wall modifications (Abu-Goukh and Bashir, 2003; Ali *et al.*, 2004).

Fruit ripening in guava is accompanied by significant changes in biochemical composition. The concentrations of soluble solids and total sugars increase during

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fruit ripening in guavas (El Bulk *et al.*, 1997; Bashir and Abu-Goukh, 2003; Singh and Pal, 2008a; Singh and Pal, 2008b). Generally, fructose is the predominant sugar in ripe guava, followed by glucose and sucrose. The individual sugar profiles vary from cultivar to cultivar (Wilson *et al.*, 1982; El Bulk *et al.*, 1997). In general, titratable acidity and total phenolics decrease during fruit ripening (Paull and Goo, 1983; Tandon *et al.*, 1989; Bashir and Abu-Goukh, 2003; Singh and Pal, 2008b; Singh and Pal, 2009). Citric acid is the major organic acid, followed by malic and glycolic acids (Wilson *et al.*, 1982). Ascorbic acid concentrations increase significantly during the initial stages of fruit ripening and then decrease with senescence (Rathore, 1976; El Bulk *et al.*, 1997; Soares *et al.*, 2007; Gomez and Lajolo, 2008). The increase in ascorbic acid during fruit ripening in guava has been associated with the increased activity of L-galactono-1,4-lactone dehydrogenase, a key enzyme in the ascorbic acid biosynthetic pathway. The activity of dehydroascorbate reductase, which acts to reduce dehydroascorbate into ascorbate, also increases during the initial stages of guava fruit ripening to compensate for increased oxidation of ascorbate by ascorbate peroxidase (Gomez and Lajolo, 2008).

Guava fruit has a strong characteristic aroma due to esters and terpenes. In mature fruit, the esters (*Z*-3-hexenyl acetate, *E*-3-hexenyl acetate, ethyl hexanoate, and ethyl butanoate), 1,8-cineole, monoterpenes (myrcene and limonene) and sesquiterpenes (caryophyllene, α-humulene and β-bisabollene) are the predominant aroma compounds (MacLeod and Troconis 1982; Chyaui *et al.* 1992; Soares *et al.* 2007). The key aroma compounds of guava fruit contributing to a green, grassy odour note are (*Z*)-3-hexenal and, to a lesser extent, hexanal; 3-sulfanyl-1-hexanol and 3-sulfanylhexyl acetate impart the sulphury, tropical note; and 4-hydroxy-2,5-dimethyl-3(2*H*)-furanone, ethyl butanoate and cinnamyl acetate predominantly account for the sweet, fruity and flowery aroma (Steinhaus *et al.*, 2009). In general, the abundance of aroma-volatile compounds increases during fruit ripening.

10.3 Maturity indices

Harvesting at optimum stage is an important step to ensure the supply of a flavoursome and nutritious fruit to the consumer. Fruit flavour is significantly influenced by harvest maturity, and the advancement of fruit maturity leads to accumulation of sugars, increase in ascorbic acid, decrease in phenols and acids, and biosynthesis of aroma volatile compounds (El Bulk *et al.*, 1997; Bashir and Abu-Goukh, 2003; Soares *et al.*, 2007). Excessive delays in harvesting reduce the potential shelf-life of guava (Tandon *et al.*, 1989). Changes in fruit skin colour and size have been recommended as the best harvest maturity indices (Mercado-Silva *et al.*, 1998; Singh and Pal, 2008a; Singh and Pal, 2008b). The change in fruit skin colour from dark green to light green coupled with attained fruit size are useful indices to determine harvest maturity. Other maturity indices such as specific gravity, chemical attributes and fruit detachment force have been found

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beneficial for determining the harvesting stage (Kumar and Hoda, 1974; Rathore, 1976; Paull and Goo, 1983; Tandon *et al.*, 1989; Mercado-Silva *et al.*, 1998). Specific gravity decreases during the final phase of fruit maturation in guava. The fruit quality and consumer acceptability of guava harvested at specific gravity <1.0 had been better than those harvested at 1.00–1.02 (Tandon *et al.*, 1989). A large variation in specific gravity among fruit lots, seasonal variations and the cumbersome procedure of grading according to specific gravity limit its usefulness as a single maturity index (Kumar and Hoda, 1974; Mercado-Silva *et al.*, 1998). Chemical attributes such as SSC, titratable acidity (TA) and tannin content may be used as additional maturity indices (Yusof and Mohamed, 1987). Seasonal and cultivar variations in SSC and other chemical attributes also limit their application in making harvest decisions (Rathore, 1976). Therefore, under a given set of agroclimatic conditions, the visual appearance of fruit on the basis of skin colour and size may serve as the best maturity indicator. In general, the fruit must be physiologically mature at harvest to achieve proper fruit ripening. Immature fruit will either fail to ripen or become senescent before reaching marketable quality.

10.4 Preharvest factors affecting fruit quality

10.4.1 Effects of fruiting season

Seasonal conditions can have a considerable influence on fruit maturation and quality of guava fruit. The rate of fruit growth in guava is inversely related to prevailing temperatures during the growing season (Rathore, 1976; Mercado-Silva *et al.*, 1998). Therefore, fruit in the autumn–winter season take a longer time to reach full maturity than in spring–summer. In general, fruit quality of the winter crop is superior to those grown during the summer and rainy seasons. The fruit quality attributes such as SSC, TA, firmness and ascorbic acid concentration are generally better in the winter season crop. The increased accumulation of chemical constituents during the autumn–winter season could be attributed to the effect of low temperature on the retardation of the excessive loss of substrates due to respiratory activity and also due to increased translocation of photosynthates from leaves to the fruits (Rathore, 1976). Furthermore, the postharvest life of autumn–winter guava is also longer than the spring–summer ones as the number of days to reach respiratory and ethylene climacteric peaks has been reported to be 7–8 days in the former and 5 days in the latter (Mercado-Silva *et al.*, 1998). In addition to inferior fruit quality, the rainy season guava fruit are more prone to insect-pests and diseases. The population of fruit flies during hot and humid conditions is high and causes serious economic losses for the guava growers (Singh and Pal, 2007). To counteract the fruit fly problem, growers are advised to regulate the crop to avoid production during the rainy season (Kumar and Hoda, 1977). This practice induces profuse flowering during the winter season and the growers earn better prices due to higher yields and superior fruit quality.

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10.4.2 Effects of orchard practices

The cultural operations followed in guava orchards significantly influence fruit quality and postharvest life. A study conducted in the semi-arid irrigated zone of the Punjab state in India has shown that the method of irrigation influenced fruit quality in the 'Allahabad Safeda' cultivar (Mandal *et al.*, 2007). The trees subjected to drip irrigation produced larger fruit with higher sugar and ascorbic acid content compared to flood-irrigated trees. The tree spacing of the same cultivar at either 5×5 m or 6×6 m did not influence the fruit quality parameters. Mulching material has been shown to positively influence fruit quality in 'Lucknow-49' cultivar (Dutta and Majumder, 2009). Postharvest storage life was also improved when the trees were mulched using 50 μm thick black polyethylene compared to control (no mulching) and other mulching materials such as paddy husks. Guava trees are generally pruned to train the tree, control vegetative growth, remove diseased twigs and shoots and improve light penetration into the fruit canopy. The pruning of 'Lucknow-49' cultivar during rainy and winter seasons at 30 cm from the shoot tip increased fruit size, SSC and ascorbic acid content (Singh and Dhaliwal, 2004). The effects of rootstock on fruit quality of commercial cultivars have not been investigated in much detail. Singh *et al.* (1976) evaluated different species of *Psidium* as rootstocks, and found that grafting of 'Allahabad Safeda' on *Psidium pumilum* increased sugar content in fruit, while higher ascorbic acid content was observed on *P. cujavillis*.

Preharvest bagging is a technique used to control damage from birds, insects and diseases, and also to protect the fruit from extreme temperatures, thereby improving the appearance of fruit. The final phase of fruit growth in winter season guava is slow and results in uneven fruit maturity. The bagging of 'Allahabad Safeda' fruit with paper bags, one month prior to harvest, advanced fruit maturity and resulted in attractive skin colour development, improved quality in terms of high ascorbic acid and SSC with lower levels of acidity (Singh *et al.*, 2007). However, the higher postharvest rates of respiration and ethylene production in bagged fruit were associated with a reduction in shelf-life of 3 days compared to non-bagged fruit. This technique can be very useful to produce high quality and premium fruit for export markets, if postharvest ripening is regulated properly.

10.4.3 Canopy position and tree age

Canopy position is one of the factors contributing to heterogeneity in the fruit quality. 'Allahabad Safeda' fruit picked from the upper canopy of 15-year-old trees had higher SSC and lower acidity than those picked from middle and lower canopies (Asrey *et al.*, 2007). On the other hand, the fruit from the lower and middle canopies showed higher ascorbic acid content than those from the upper canopy. Seed content in fruit also varied with tree age, and it decreased with increasing tree age from 10 to 20 years. The mineral composition of fruit was also found to vary with tree age (Asrey *et al.*, 2007), but this report was not conclusive.

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More research is required to confirm the effects of these factors on quality and storage behaviour of guava fruit.

10.4.4 Preharvest applications of mineral nutrients, growth regulators and other chemicals

The soil and foliar applications of macro and micronutrients can potentially affect fruit quality and postharvest storage behaviour of guava. Among the primary nutrients, potassium plays a significant role in improving fruit quality in terms of increased SSC, ascorbic acid and lower acidity (Mitra and Bose, 1985; Kumar *et al.*, 1996). Higher doses (260 g/tree) of potassium fertilizer increased the SSC; on the other hand, increased rates of nitrogen application (260 g/tree) decreased the SSC and phosphate fertilizers showed no marked effect (Mitra and Bose, 1985). The preharvest foliar applications of calcium, zinc and boron also give beneficial results in terms of improvement in fruit size, SSC and ascorbic acid. Spraying 'Lucknow-49' fruit, three weeks before harvest, with alar [daminozide] (500 or 1000 ppm) or calcium nitrate (2%) resulted in reduced weight loss, increased firmness and a lower level of decay when these fruit were held at 27 °C for up to 8 days (Singh and Chauhan, 1982). Soil amendment practices can also affect the quality of guava fruit. A study in Brazil showed that application of lime to an acid soil before tree planting increased calcium levels in guava fruit and resulted in reduced weight loss and titratable acidity, and better firmness retention during postharvest storage (Prado *et al.*, 2005). The preharvest application of various plant growth regulators (PGR) can either enhance or delay fruit ripening processes. Jayachandran *et al.* (2005) evaluated the effects of preharvest sprays of growth regulators, naphthaleneacetic acid (NAA; 100 and 200 ppm), 2,4-dichlorophenoxyacetic acid (2,4-D; 5 and 10 ppm) and gibberellic acid (GA_3; 50 and 100 ppm), on the shelf-life and quality of 'Lucknow-49' guava stored at 28–32 °C in 300 gauge polyethylene bags with 0.1 % ventilation. The postharvest shelf-life, quality and resistance to rotting were better in fruit treated with 100 ppm GA_3 than NAA and 2,4-D. The postharvest dipping of mature green 'Allahabad Safeda' guava fruit in gibberellins at 100 or 200 ppm also retarded weight loss and fruit ripening, while dipping in 2,4-D and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) at 100 ppm accelerated fruit ripening and weight loss (Saha, 1971). The pre or postharvest application of PGRs to manipulate fruit ripening in guava is not a commercial practice.

10.5 Postharvest handling factors affecting fruit quality

10.5.1 Temperature management

Guava fruit are highly perishable. The postharvest life of guava fruit under ambient conditions varies from 6–8 days. Low-temperature storage is the most practical way to slow physiological processes like respiration and ethylene production. Therefore, storing fruit at an optimum temperature range is the most

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important factor in maintaining fruit quality and minimizing postharvest losses. Storage temperatures low enough to significantly slow fruit metabolism can cause chilling injury (CI) in tropical fruit and, if high enough to avoid CI, often accelerate or do not affect the process of fruit ripening and do not increase shelf-life or maintain quality (Singh, 2010). Guava fruit can be stored at 8–10 °C for 2–3 weeks (Reyes and Paull, 1995). Storage of guava fruit below the critical storage temperature of 8–10 °C can cause CI symptoms (Reyes and Paull, 1995; González-Aguilar *et al.*, 2004). On the other hand, storage at recommended temperature can also cause CI if the storage duration is prolonged (Singh and Pal, 2008a; Singh and Pal, 2008b). The tolerance to chilling temperature depends upon many factors including cultivar, harvest season, maturity status and length of storage. CI is discussed in detail in section 10.6. It is proposed that fruit harvested at the colour turning stage, a commercial practice in most of the guava producing countries, should not be stored for more than 2–3 weeks at 8 to 10 °C. These could be stored at 15 °C to allow gradual ripening and to delay deterioration of quarter-yellow and half-yellow fruit before processing (Reyes and Paull, 1995).

10.5.2 Physical damage

Physical damage is one of the major causes of economic losses of guava fruit. The fruit are very delicate and cannot withstand rough handling during harvest and postharvest operations (Singh, 2010). The fruit skin is thin and offers little resistance to mechanical injuries such as cuts, punctures, bruising and impact and compression damage. The severity of such injuries depends upon the harvesting method and postharvest handling procedures. These injuries can increase water loss, cause skin browning and also serve as entry points for various decay-causing microorganisms (Ko and Kunimoto, 1980). Mechanical injuries causing skin browning may even penetrate into the flesh also. Polyphenol oxidase (PPO) catalyzes browning reactions in most fresh produce and has also been isolated from guava fruit (Augustin *et al.*, 1985). The disruption of cell membranes by injuries may result in mixing of PPO with phenolic compounds leaking out of the vacuole leading to skin browning. Skin browning reduces the visual quality of fruit as it should be practically free of such defects to meet high quality standards.

The tomographic images from magnetic resonance imaging (MRI) of whole guava fruit subjected to impact damage by free-fall from a height of 1.2 m showed that the pericarp was intact, but cellular integrity was lost and the placenta tissue had liquefied (Durigan *et al.*, 2005). On the other hand, compression damage imposed by applying a force of 29.4 N for 15 min produced lesions in the external pericarp, but internal tissue remained intact due to resistance provided by the structure and elasticity of guava fruit tissues. This study clearly shows that MRI can be used for non-destructive evaluation and grading of guava fruit for physical injuries. To avoid physical injuries, wrapping individual fruit with paper is a common practice for long-distance shipping. Cultivar type also influences the susceptibility of fruit to physical damage. For example, 'Pedro Sato' has been reported to be more susceptible to impact damage than 'Paluma' (Mattiuz *et al.*,

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2002). Therefore, harvesting and packinghouse operations should be undertaken very carefully, because avoiding such defects can decrease the microbial infections.

10.5.3 Water loss

Water loss or desiccation is another postharvest problem affecting quality in guava fruit. Weight loss during storage at ambient conditions is faster and higher compared to cold storage. During 6–8 days of shelf-life, fruit may lose 10–20% of its initial weight depending upon the temperature and RH of the environment. Desiccation results in shriveling and loss of texture rendering the fruit unacceptable to the consumer. Modified atmosphere packaging (MAP) and edible coatings can reduce weight loss during storage and shelf-life of fruit.

Modified atmosphere packaging (MAP)

Weight loss by guava fruit can be substantially reduced by application of MAP technology (Combrink *et al.*, 1990; Gaspar *et al.*, 1997; Jacomino *et al.*, 2001a; Jacomino *et al.*, 2001b; Pal *et al.*, 2004). Guava fruit cv. 'Fan Retief' packed into non-perforated polyethylene bags (35 μm thickness) impregnated with a natural mineral compound may be stored for 1 week at 20 °C or for 2 weeks at 4.5 °C without appreciable loss of quality (Combrink *et al.*, 1990). The results of MAP studies generally vary due to variation in the storage conditions, and the thickness of the films used by different researchers. For example, MAP of guava fruit cv. 'Kumagai' in 24.7 μm thick low density polyethylene (LDPE) film resulted in reduced weight loss, lower acidity and SSC, and lower CI symptoms during 3 weeks of storage at 8 °C (Gaspar *et al.*, 1997). The fruit of the same cultivar packed in a thicker LDPE film (69 μm) created an atmosphere very low in O_2 (0.1 kPa) and high in CO_2 (19 kPa) during storage at 10 °C for 3 or 4 weeks, and the fruit developed an intense off-flavour in addition to a substantial loss of ascorbic acid caused by high CO_2 (Jacomino *et al.*, 2001a; Jacomino *et al.*, 2001b). Based on these studies, packaging of guava fruit in 10–35 μm thick LDPE film in conjunction with low temperature can be recommended to reduce weight loss and maintain fruit quality.

There is a potential for individual shrink-wrapping of guava fruit to reduce weight loss during storage and shelf-life. Mohamed *et al.* (1994) reported that shrink-wrapping of 'Vietnamese' guava with LDPE (25 μm thickness) film was more effective in reducing weight loss, maintaining flesh firmness and retarding skin colour changes compared to cling-wrap packaging (10 μm thick LDPE) during 7 weeks storage at 10 °C. Pal *et al.* (2004) reported that 'Lucknow-49' guava individually shrink-wrapped using 9 μm linear LDPE film could be stored for up to 12 and 18 days at ambient and in an evaporatively cooled chamber (8–12 °C), respectively. Temperature abuse during handling, storage and transportation may favour large changes in the fruit respiration rate but a small change in film permeability leading to low O_2 and high CO_2 inside the packs. Consequently, fruit respiration may shift from aerobic to anaerobic metabolism due to low O_2 and high

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CO_2 which can induce the accumulation of anaerobic metabolites, ethanol and acetaldehyde, leading to development of off-flavour in the fruit. Thus, it is essential both to avoid temperature fluctuations and to design MA packages to compensate for temperature fluctuations with use of highly permeable materials. The reliability of MAP will depend upon the physiological status of fruit, film thickness and permeability, and storage conditions (Singh, 2010). More research is required to integrate the use of natural compounds/extracts with antimicrobial properties with MAP systems in order to eliminate the use of synthetic fungicides.

Surface coatings
Edible coatings may be used to reduce the rates of water loss, retard fruit ripening, maintain texture of fruits and inhibit microbial growth (Kester and Fennema, 1986). Edible coatings can also be used as a carrier of functional ingredients such as antioxidants, antimicrobial compounds and calcium salts. Coating with 5% carnauba was found to be most effective in reducing weight loss and retaining fruit firmness (McGuire and Hallman, 1995). The rate of fruit softening in guava coated with 2% and 4% hydroxypropylcellulose (HPC) was reduced by 35% and 45%, respectively. The application of Sta-fresh™, a carnauba wax based coating, was effective in reducing weight loss and ethylene production during storage of 'Lucknow-49' guava at ambient conditions and in an evaporative cool chamber (8–12 °C) for 7 and 14 days, respectively (Pal *et al.*, 2004). Individual shrink-wrapping has been reported to be more effective than edible coatings in reducing weight loss (Mohamed *et al.*, 1994; Pal *et al.*, 2004). The future expansion of coating materials and formulation techniques offers opportunities for further increase in the use of tailored edible coatings for retaining fruit quality in guava (Singh, 2010).

10.5.4 Storage atmosphere

Controlled/modified atmospheres (CA/MA) are known to extend the postharvest life and maintain fruit quality in addition to other benefits such as alleviation of CI in many tropical and subtropical fruits including guava (Singh *et al.*, 2009; Yahia, 1998; Yahia and Singh, 2009). The responses of guava fruit to short- and long-term MA storage have been found positive to extend postharvest life and maintain quality.

Short-term MA exposure
Short-term exposure to low O_2 (< 1–10 kPa) and high CO_2 (5–40 kPa) atmospheres has potential to improve postharvest life. Short-term exposure of guava fruit to high CO_2 levels (10, 20 and 30 kPa) reduced ethylene evolution during ripening, but did not influence respiration rates (Pal and Buescher, 1993). Similarly, treating guava with 10 kPa O_2 + 5 kPa CO_2 for 24 h before storage in air at 4 °C for 2 weeks reduced CI symptoms and delayed color development in fruit compared with fruit held in air (Bautista and Silva, 1997). A preliminary study on the short-term exposure of guava fruit to very low O_2 (<1 kPa) and high CO_2 (40 kPa) at

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40 °C for 12 h has shown that this treatment is beneficial to extend the shelf-life of fruit by 2–3 days at ambient conditions and may find application in postharvest insect-pest disinfestation procedures for quarantine purposes (Singh and Pal, 2007). Guava (cultivar not given) fruit artificially inoculated with spores of *Rhizopus stolonifer* (Ehrenberg: Fries), then held in 80% nitrous oxide (N_2O) for 6 days showed no disease symptoms, while the symptoms appeared after 2.2 days when fruit were held in normal air (Qadir and Hashinaga, 2001). This study indicated the potential of a non-conventional gas in reducing decay in fresh fruit, but its commercial use may not be possible because of concerns for handlers' safety.

Controlled atmosphere (CA)
According to Kader (2003), guava fruit can be stored or transported in an atmosphere containing 2–5 kPa O_2 and 0–1 kPa CO_2 at 5–15 °C. CA has been found useful in maintaining harvest freshness and alleviating CI in guava fruit (Singh and Pal, 2008a). Singh and Pal (2008a) found that atmospheres containing O_2 less than 5kPa were injurious for visual and flavour quality of 'Lucknow-49' and 'Allahabad Safeda', while 'Apple Colour' did not tolerate O_2 atmospheres below 8 kPa. The ideal CA storage conditions for three cultivars, 'Lucknow-49', 'Allahabad Safeda' and 'Apple Colour', were 5 kPa O_2 + 2.5 kPa CO_2, 5 kPa O_2 + 5 kPa CO_2, and 8 kPa O_2 + 5 kPa CO_2, respectively, at 8 °C. Under these CA conditions, fruit were stored for 30 days at 8 °C without significant CI symptoms and fruit ripened at ambient conditions in 5 days. CA storage significantly reduced the respiration and ethylene production rates during a post-CA storage period of 5 days at ambient conditions (25–29 °C). CA storage was also found effective in reducing ascorbic acid loss during 30 days storage and the extent of ascorbic acid loss decreased as O_2 level decreased, but high CO_2 did not favour its retention. Fruit firmness was retained in CA-stored fruit for 30 days, but the differences in the firmness, irrespective of storage atmosphere, were non-significant after 5 days at ambient conditions. Therefore, CA has potential to extend the postharvest life and overcome CI of guava fruit during storage and shipping (Singh and Pal, 2008a).

Guava is very sensitive to anaerobiosis resulting from low O_2 and/or high CO_2 (McGuire and Hallman, 1995; Pesis, 2005; Yahia, 1997). Low levels of O_2 in the storage atmosphere can potentially cause accumulation of anaerobic metabolites, ethanol and acetaldehyde (AA), in guava fruit. Singh *et al.* (2008a) reported that atmospheres low in O_2 (2.5 kPa) caused a differential increase in the concentrations of ethanol and AA in three guava cultivars. The levels of these metabolites differed among three cultivars, possibly due to differences in the gas exchange properties of peel and flesh tissues. Singh (2010) suggested that acetaldehyde accumulation during CA storage and its increase during ripening might be contributing to the aroma volatiles biosynthesis in guava in addition to its role in the removal of astringency from guava fruit. According to my proposed model on the effects of CA/MA in guava, there is a possibility that suppression of ethylene production and respiration during ripening of CA-stored guava and alleviation of CI could be due

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to the high ethanol and acetaldehyde concentrations in fruit (Singh, 2010), as the role of these anaerobic metabolites in modifying these physiological processes has already been recognized (Pesis, 2005). Further research is required to elucidate the roles of these compounds in guava fruit ripening and physiology. CA storage may used for marine transport of guava to distant markets which may take 2 or 3 weeks (Singh *et al.*, 2009; Singh, 2010). The CA requirements need to be appraised for storing and transporting guava at temperatures other than 8 °C as the changes in storage temperature may possibly alter the CA optima. Genotypic variation in the responses of guava to CA necessitates further investigations on other cultivars.

10.6 Physiological disorders

Chilling injury (CI) is a physiological disorder resulting from exposure of fruit to temperatures below a critical limit for a period longer than a certain threshold (Paull, 1999). Susceptibility of guava fruit to CI limits storage life and distribution at low temperatures (Singh, 2010). The most common symptoms of CI in guava are surface pitting, water-soaked lesions, external and internal discolouration, uneven fruit ripening and enhanced decay (Reyes and Paull, 1995; González-Aguilar *et al.*, 2004; Singh and Pal, 2008a; Singh and Pal, 2008b; Singh and Pal, 2009). CI symptoms including surface pitting, skin browning and water-soaked lesions appearing during cold storage, but the severity of these symptoms increases upon transfer to ambient conditions (Singh and Pal, 2008a; Singh and Pal, 2008b). The severity of CI depends upon the storage temperature, the duration of storage and the sensitivity of the cultivar to chilling temperatures (Paull, 1999).

Storage temperature is the predominant factor influencing development of CI symptoms in guava fruit (Reyes and Paull, 1995; Tiwari *et al.*, 2006). 'Allahabad Safeda' fruit stored at 5°C for 2 weeks showed skin bronzing and failed to ripen properly when transferred to ambient conditions. Electrolyte leakage from fruit sample tissue increased with the severity of CI, demonstrating the disruption of cell membranes by CI (González-Aguilar *et al.*, 2004; Tiwari *et al.*, 2006). Fruit maturity influences susceptibility of guava to CI. For instance, guava fruit harvested at the colour turning stage could be stored for 3 weeks at 7 °C with good appearance and less decay than those harvested at a mature-green stage (Vazquez-Ochoa and Colinas-Leon, 1990). The supplementation of low temperature storage, either with some postharvest treatments (chemical, physical, and biological) or with modified atmospheres (low O_2 and high CO_2), can have synergistic effects in alleviating CI (Singh, 2010). CI in guava fruit has been alleviated by short-term exposure to CA or long-term static CA and MAP. Like many other fruits, guava has been reported to benefit from the postharvest application of 1-MCP with regard to CI. 1-MCP treatment at 300 nL L^{-1} for 12 h or 600 nL L^{-1} for 6 h reduced CI symptoms in 'Allahabad Safeda' during 25 days of cold storage at 10 °C plus 5 days at 25–29 °C (Singh and Pal, 2008b). Pre-storage treatment of guava fruit with methyl jasmonate vapours (10^{-4} M or 10^{-5}M) also reduced CI symptoms during storage at 5 °C for 15 days (González-Aguilar *et al.*, 2004). Heat

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treatments can also induce resistance to CI in some tropical fruits. Guava fruit are reported to be sensitive to heat treatments ranging from slight to severe effects on fruit quality (Gould and Sharp, 1992; Yusof and Hashim, 1992; Monzon *et al.*, 2005). It is therefore not feasible to use high temperature treatments to induce chilling tolerance in guava fruit. The biochemical and molecular basis of CI in guava fruit remains unclear. It is therefore important to avoid storage at chilling temperatures throughout the supply chain.

10.7 Postharvest pathological disorders

Postharvest pathological problems are very common and severe in tropical fruits, such as guava, due to hot and humid conditions at harvest and during distribution. Fruit rots can appear on mature and ripening fruit prior to harvest, at harvest and during transportation and storage. Anthracnose, caused by *Colletotrichum gloeosporioides*, is the most common fungal disease causing severe postharvest losses in guava (Lim and Manicom, 2003). The symptoms of anthracnose appear in the form of small brown lesions on the fruit surface, which later grow into large and sunken patches. There are several other types of fruit rots observed after harvest. Lim and Manicom (2003) classified these rots into dry and soft types. Dry rots produce necrotic lesions that are shallow and superficial, and restricted to either small spots or patches. On the other hand, soft rots appear as water-soaked areas that expand and extend into the fruit mesocarp or even into the seed cavity. Dry rots are mostly caused by *Cladosporium* sp., *Diplodia theobromae*, *Guignardia* sp., *Macrophoma* sp. and *Macrophomina phaseolina*, while soft rots are caused by several other fungal pathogens such as *Aspergillus niger*, *Rhizopus stolonifer*, *Mucor heamalis*, *Fusarium solani*, etc.

In some rots such as anthracnose, Phytophthtora fruit rot and stylar end rot (Phomopsis rot), the pathogens invade the developing fruit in the orchard, but the infection remains quiescent until the fruit are harvested. The proliferation of fruit rots is enhanced by the changes during fruit ripening such as a decrease in natural antifungal compounds and phytoalexins, increase in sugars that serve as the food base for pathogens, decrease in phenolics that are vital to provide resistance against pathogens, and softening that facilitates the breakdown of tissue by fungi (Prusky, 1996). Physical damage to fruit during harvest and postharvest operations is primarily responsible for the loss of integrity of natural barriers that are otherwise effective to prevent infection by secondary pathogens.

The development of fruit rots can be considerably reduced by effective cold-chain management. The activity of most of the fungal pathogens is suppressed by low temperature storage (Prusky, 1996). Storage at temperature below a critical limit can induce chilling damage that further enhances the susceptibility of fruit to decay. Careful harvesting and handling procedures should be adopted to reduce physical damage which in turn can decrease the occurrence of infections (Ko and Kunimoto, 1980). Postharvest treatments that are known to delay fruit ripening can possibly delay the onset of disease. For instance, 1-MCP treatment has been

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reported to reduce the decay incidence in guava fruit (Singh and Pal, 2008b). Similarly, exposure of mature unripe guava fruit to gamma irradiation (0.25–0.5 kGy) has potential to reduce fruit decay (Singh and Pal, 2009). Maximizing storage life of most tropical fruits requires treatment with a fungicide. The fungicides are most effective when the treated fruit has intrinsic resistance to infection and environmental conditions are least favourable for growth of the pathogen (Eckert and Ogawa, 1985). Therefore, a combination of postharvest fungicide treatment and optimum storage conditions is essential to reduce the incidence of fruit rots in guava. Preharvest fungicide sprays and good orchard management practices are crucial to reduce latent infections in the developing fruit. In general, a single postharvest treatment may not be adequate to effectively control all postharvest diseases. The choice of fungicide type and treatment dose depends on the availability of fungicides approved for use in a particular country, the fungicides used in the field sprays and the destination market for the fruit (Singh, 2010). Several fungicides such as benomyl, carbendazim, triforine, prochloraz and mancozeb have given satisfactory disease control in guava fruit. The rotting of fruit of four guava cultivars was considerably reduced by dipping the fruit after harvest in hot benomyl (0.5–2.0 g L^{-1}) at 48–50 °C for 5 min, while heated guazatine was phytotoxic and less effective than benomyl (Wills *et al.*, 1982). Fruit rots caused by *Aspergillus* have been controlled by carbendazim and triforine, both at 1.25 g L^{-1} (Arya *et al.*, 1981). Prochloraz is a broad-spectrum imidazole fungicide permitted for postharvest use in fruits in many countries. The rotting of guava caused by *Colletotrichum gloeosporioides* [*Glomerella cingulata*] and *Phomopsis anonacearum* was significantly reduced by dipping the fruits in solutions of prochloraz (0.125–0.25 g L^{-1}) at room temperature (~25 °C) for 5 sec to 5 min (Brown *et al.*, 1984). Prochloraz may cause skin injury, particularly on white-fleshed guava, and was not effective against *Rhizopus stolonifer*. Gupta and Mukherjee (1980) reported that morphactin (chlorflurenol methyl ester 74050 [chlorflurecol]) applied at a concentration of 100 mg L^{-1} to guava fruits cv. 'Allahabad Safeda' was effective in reducing weight loss, fungal decay, chlorophyll breakdown and loss in firmness. Guava has been reported to be very sensitive to copper-induced phytotoxicity (Gaikwad and Nimbalkar, 2005). The pre or postharvest application of copper-containing fungicides, such as Bordeaux mixture and copper oxychloride, to guava fruit should be used carefully considering their phytotoxic effects.

Synthetic fungicides have been commonly used to control postharvest diseases in guava. The development of pathogen resistance to a wide range of fungicides has stimulated research towards more resilient and ecofriendly postharvest disease management practices such as application of natural compounds and biological control. The exposure of mature green 'Banarsi Surkha' guava to ethanol and acetic acid vapours for 2 hours reduced microbial load on fruit and improved shelf-life (Siddiqui *et al.*, 2005). Biological control using microbial antagonists can be used as a part of an integrated postharvest disease management strategy to reduce the use of synthetic fungicides. A recent study has shown that strains of yeast (*Pichia anomala* Moh93, *P. anomala* Moh104) were most effective against

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fruit rot of guava caused by *Botryodiplodia theobromae* (Hashem and Alamri, 2009). The production of cellulase and pectinase enzymes was significantly inhibited in guava fruit infected with *B. theobromae* when yeast strains were applied. This study also showed the potential of strains of the yeast *P. anomala* as a safe and effective biocontrol agent against postharvest rot of guava fruit caused by *Diplodia* sp. The application of two antagonistic yeasts (*Candida* sp. and *Rhodotorula* sp.) controlled the predominant pathogens, *Penicillium expansum* and *Pestalotiopsis psidii*, more effectively when used individually than in combination (Deeba *et al.*, 2008). The efficacy of these biological control agents can be further improved by applying them in combination with low concentrations of a recommended fungicide and other physical treatments. The antagonists applied just before harvest can precolonize the fruit surface so that wounds inflicted during harvest can be colonized by the antagonist before the invasion of the pathogen (Janisiewicz and Korsten, 2002). This approach could be very useful to prevent fruit rots caused by secondary infection in guava fruit. Future research is required to determine the efficacies of various biocontrol agents against a range of pathogens and under different growing and postharvest conditions.

10.8 Postharvest insect-pests and phytosanitary treatments

Guava is a host for several species of insect-pests. Fruit flies are the most important pests of guava worldwide and cause severe economic losses (Gould and Raga, 2002). *Bactrocera correcta* (Bezzi), often referred to as 'the guava fruit fly', is mainly distributed in India, Nepal, Pakistan, Sri Lanka, and Thailand. In tropical America, guava hosts several other fruit fly species, which include Caribbean fruit fly (*Anastrepha suspense* Loew), Mexican fruit fly (*A. ludens* Loew), West Indian fruit fly (*A. oblique* Macquart) and *A. striata* Schiner. In addition to the fruit flies, guava fruit are also attacked by fruit borers, thrips, mites and scale insects. Under integrated pest management (IPM) programmes, the physical, chemical, cultural and biological control of these insect-pests is recommended for economic production of guava. Fruit bagging is the best method to control the Caribbean fruit flies in Florida, US (Peña *et al.*, 1999). Discussion of preharvest IPM is beyond the scope of this chapter. The main focus is on postharvest treatments to control these insect-pests from a quarantine perspective.

10.8.1 Heat and cold treatments

Most of the insect-pests of guava are highly regulated by the phytosanitary requirements of many countries. The main objective of a phytosanitary treatment is to prevent the introduction or spread of pests (Hallman and Loaharanu, 2002). This is a great hindrance in the commercialization of guava in the international trade. Several postharvest treatments including heat, cold and irradiation have been tested and found to be effective in disinfesting guava fruit. Hot-water treatment (HWT) can be an effective way to eliminate the regulatory pests of

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guava fruit (Gould and Sharp, 1992). The immersion of guava for 32.7 min in water heated to 46 °C achieved probit-9 mortality (99.999 %) of the third-instar larvae of *Anastrepha suspensa* (Loew). Additionally, hot-water treated fruit kept at 10 °C maintained acceptable quality 7 days longer than those held at 24 ± 2 °C (Gould and Sharp, 1992). The waxing of fruit immediately after HWT exacerbated chilling injury, further delayed ripening with a concomitant increase in the percentage of fruits that did not ripen, and caused fruit to remain greener (McGuire, 1997). But delaying the waxing of heat-treated guava or reconditioning them for 24 h at 20 °C before cold storage promoted normal ripening and helped to maintain the quality of the heat-treated fruit. Vapour heat treatment (VHT) is another method of postharvest heat application in which fruit is exposed to heated air at high relative humidity, and is a recognized phytosanitary treatment for tropical fruits like mango in some countries. VHT at 46 °C for 10 min was sufficient to kill the fruit fly larvae in 'Kampuchea' guava, and similar to HWT, it resulted in loss of ascorbic acid, chlorophyll and skin scorching, particularly around the stalk area (Yusof and Hashim, 1992). VHT resulted in more fruit softening than HWT. Heating of guava fruit by the application of radio-frequency energy also caused external browning in the form of circular brown spots on the skin (Monzon *et al.*, 2005).

Cold disinfestation treatment requires the fruit to be exposed to very low temperatures for a period ranging from several hours to a few days. The application of cold treatment as a disinfestation procedure is not possible for guava because the fruit are chilling sensitive. Cold treatment of guava at 1.1 °C for 15 days, which was necessary for disinfestation of *A. suspense*, caused unacceptable blackening of the fruit surface (Gould, 1994). Based on these studies, the prospects for application of heat or cold as a single quarantine treatment are not encouraging.

10.8.2 Irradiation

Irradiation is another phytosanitary treatment that can ensure the control of potentially invasive insect-pests. In contrast to thermal and cold treatments for phytosanitation, irradiation is more tolerated by fresh fruits with a minimal loss of quality (Hallman and Loaharanu, 2002). In 2002, irradiation was approved as a phytosanitary treatment for all admissible fresh fruits and vegetables from all countries into the United States (USDA, 2007). The Animal and Plant Health Inspection Service (APHIS) of the USDA has approved irradiation with a minimum generic absorbed pest dose of 150 Gy as a treatment for all tephritid fruit flies in fruit, a minimum dose of 400 Gy for all other insects, except Lepidoptera pupae and adults (USDA, 2007). The guava to be imported must be part of a commercial shipment and irradiated with a minimum absorbed dose of 400 Gy (USDA, 2008a). In addition to irradiation, some mitigatory measures have to be followed in order to reduce the potential risks associated with the quarantine pests. These mitigatory measures include production of guava for export within pest-free areas or areas of low pest prevalence, mechanical, chemical and cultural pest control programmes in guava orchards, field and

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phytosanitary inspection, sampling and testing procedures during the production season, packinghouse procedures and quarantine treatments to disinfest fruit, consignments traceable to place of origin, point-of-entry sampling and inspection limits on distribution and transit within the United States (USDA, 2008b).

The extended postharvest life of fruit in response to irradiation treatment can be considered as an additional benefit. Guava has been classified among the fruits which are the most tolerant to ionizing radiation doses of less than 1 kGy (Kader, 1986). Ionizing radiation treatment extends the postharvest life and reduces decay incidence in guava fruit (Thomas, 1988; Singh and Pal, 2009). Ionizing radiation treatment (0.25 kGy) suppressed the respiration and ethylene production rates of two guava cultivars, 'Allahabad Safeda' and 'Lucknow-49', during 8 days of shelf life at 27 ± 2 °C (Singh and Pal, 2009). The suppression of respiration and ethylene production rates increased with the increase in radiation dose from 0.25 to 1.0 kGy and suggests that guava can tolerate even high doses of ionizing radiation without manifesting stress symptoms in the form of burst of respiratory activity and ethylene. Irradiated guava, particularly cv. 'Lucknow-49', when stored for 22 days at 10 °C did not have reduced rates of respiration during their subsequent removal to ambient conditions; but ethylene production rates were significantly lower in irradiated fruit of both cultivars, 'Lucknow-49' and 'Allahabad Safeda' (Singh and Pal, 2009). Irradiation treatment at 0.25 kGy resulted in better retention of firmness, while a higher dose of 1.0 kGy increased the rate of fruit softening (Singh and Pal, 2009). The quality of irradiated guava stored at 10 °C for 22 days after transfer to ambient conditions was similar to that of non-irradiated fruit, which shows that the positive effects of irradiation treatment diminish during cold storage. Therefore, irradiation may be used without adverse effects on fruit quality to provide phytosanitary security against many insect-pests.

The recognition of irradiation of fresh guava as a quarantine treatment by APHIS facilitated the imports from Mexico into the United States in 2008. In Mexico, 257 tonnes of guava fruit were irradiated in 2008 at a facility of Sterigenics Gamma México and the tonnage increased to 3521 tonnes in 2009 (César Moreno, personal communication). In 2010, their facilities were projected to irradiate 5300 tonnes of guava fruit. In the near future, the adoption of irradiation on a commercial scale in other countries may enhance the international trade of guava fruit.

10.9 Postharvest handling practices

10.9.1 Harvest operations

Harvesting at appropriate maturity is important to ensure the supply of good quality fruit to consumers and processors. Guava fruit must be harvested at a maturity that enables the fruit to withstand transport and handling, and to arrive in satisfactory condition at its ultimate destination. Harvesting should preferably be conducted in the early morning. In most of the guava producing countries, harvesting by hand is a common practice. The amount of force needed to detach a

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fruit decreases substantially during fruit ripening from 32 to 2.2 N (Paull and Goo, 1983) and can be a guide to the pickers to pick the fruit of right maturity. Several precautions should be taken during harvesting to avoid damage to fruit, as it increases the incidence of fruit rots (Ko and Kunimoto, 1980). The pickers should be trained and instructed to harvest and handle the fruit as gently as possible. The fruit stem (pedicel) should not be pulled out while picking, because it serves as the point of entry for decay-causing microorganisms. Fruit should be picked and placed into buckets padded with a cushioning material (Mustard, 1955). Fruit should be carefully transferred from the buckets/picking bags into the field boxes. The use of field boxes is recommended, but these should not be overfilled as this may cause compression damage to the lower fruit. The pickers should empty their bags/buckets carefully because fruit are easily damaged by dropping. The use of cushioning materials at all stages of handling in different boxes or bins is strongly recommended to avoid mechanical damage to the fruit. The regular cleaning of the picking bags/boxes with chlorinated water should be carried out to minimize the chances of secondary infection to the fruit. After harvest, fruit should be protected from direct exposure to sunlight and heat. Therefore, the field boxes should be covered with insulated covers, white cloth or tarpaulins, and should be hauled without delay to the packinghouse.

10.9.2 Packinghouse practices

The packinghouse should always be maintained in a clean condition, with careful attention to water quality, personnel hygiene, cleaning of equipment and exclusion of animals. Upon arrival at the packinghouse, the fruit are carefully transferred onto a grading belt to remove the off-grade fruit. Immature and over-mature fruit, and also those showing signs of damage from physical injury or disease, are removed. During the sorting operation, magnetic resonance imaging may be used to detect internal injuries in the guava fruit (Durigan *et al.*, 2005). In Florida, the cull rate during packinghouse operations of guava can be as high as 40% (Murray and Campbell, 1989). The major reasons for rejection include ripe fruit, wind scar, scab and fruit fly damage. After sorting, the fruit is washed with chlorinated water. The application of fungicides and waxing may follow, depending upon the acceptability of these chemicals for use in a given country. Grading and sizing of guava can be done manually or by semi- or fully automated machines suitable for round fruits. According to CODEX standards for fresh guava, fruit can be graded into three classes: extra class, class I, and class II (Anonymous, 1999). Extra class fruit must be of superior quality and free from defects, with the exception of very slight superficial defects, provided these do not affect fruit appearance, quality, keeping quality and presentation in the package. Class I fruit must be of good quality, but with slight defects on the skin due to rubbing and other superficial defects such as sunburns, blemishes and scabs not exceeding 5% of the total surface area. Class II includes the fruit which do not qualify for the higher classes, but should meet minimum quality requirements including the total surface area with defects not to exceed 10%. There are nine size codes depending upon the

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fruit weight and diameter, namely 1: >450 g, >100 mm; 2: 351–450 g, 96–100 mm; 3: 251–350 g, 86–95 mm; 4: 201–250 g, 76–85 mm; 5: 151–200 g, 66–75 mm; 6: 101–150 g, 54–65 mm; 7: 61–100 g, 43–53 mm; 8: 35–60 g, 30–42 mm; 9: <35 g, <30 mm.

Fruit are generally packed in ventilated corrugated fibre board (CFB) boxes. These boxes should be lined with suitable cushioning materials to avoid injury during transit. In some developing countries, bamboo baskets lined with paddy straw, paper or wood shavings, and guava leaves are also used for packing and transportation of guava. Baskets made from other locally available plant materials are also common in these countries. Fruit should preferably be packed in CFB boxes with their pedicel end vertically upwards. Siddiqui *et al.* (1991) showed that guava fruit placed this way and held at ambient conditions showed the lowest weight loss, ethylene and respiratory rates, highest soluble solids and ascorbic acid concentrations, and were the slowest to ripen during storage. The fruit packed in lug boxes, in a single layer diagonal pack, contain 18–28 fruit per box, while three or four layers of guava can be packed in a two-fifth bushel box (Mustard, 1955). The fruit in the lower layers of a multilayered guava box are more prone to compression damage during transit. Careful handling during loading and unloading of packed guava is recommended to reduce the chances of mechanical damage to the fruit.

10.9.3 Control of ripening and senescence

Application of 1-methylcyclopropene (1-MCP), an inhibitor of ethylene perception, effectively delays ripening and senescence in many fruits (Blankenship and Dole, 2003). 1-MCP has been approved for use on guava in Brazil (AgroFresh, Inc., personal communication) and is imminent in many other countries. The beneficial effects of postharvest exposure of guava to 1-MCP include suppression of respiration and ethylene production, delayed fruit softening, restricted skin colour changes, prolonged cold storage life and alleviation of CI (Azzolini *et al.*, 2005; Bassetto *et al.*, 2005; Singh and Pal, 2008b). Postharvest exposure of 'Pedro Sato', a Brazilian guava cultivar, to 1-MCP at 300 nL L^{-1} for 6 or 12 h and at 900 nL L^{-1} for 3 h showed the best results in terms of delaying fruit ripening at ambient conditions by 3–4 days (Bassetto *et al.*, 2005). 1-MCP treatment of a climacteric-type cultivar, 'Allahabad Safeda' with 300 nL L^{-1} for 12 and 24 h or 600 nL L^{-1} for 6 h, may be used to provide 4–5 days extended marketability of fruit under ambient conditions. Treatment with 600 nL L^{-1} for 12 h is recommended for cold storage of guava fruit at 10 °C for 25 days. Most of the physiological responses during storage and ripening of guava fruit are dependent upon 1-MCP dose and exposure duration.

Although 1-MCP has been approved in at least one country, its commercial use on tropical fruits including guava appears to be limited. Many factors affect the adoption of 1-MCP based technology, which include the cost of 1-MCP relative to its benefits for the product, response of fruit to the 1-MCP treatment, scale of the industry, ease of 1-MCP integration in the supply chain, competition in the market

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and acceptance of the treated product by consumers (Watkins, 2008). The gaseous nature of 1-MCP presents operational difficulties in developing countries due to the requirements of a fumigation chamber or an air-tight tent and trained operator. The recent development of an aqueous formulation of 1-MCP may lead to increase in its use because of the ease of dipping fruit in aqueous solutions. In conclusion, 1-MCP as a postharvest tool may be integrated into the supply chain management of guava fruit to control its ripening for extended storage life and maintaining fruit quality.

10.9.4 Recommended storage and shipping

Fruit storage and shipping at low temperature is recommended to retard ripening of guava. The optimum storage conditions for guava are 8–10 °C temperature and 90% relative humidity. Storage at low temperature allows 2–3 weeks for shipment of guava to distant markets. Chilling damage to fruit can occur in the form of skin discolouration and failure of fruit ripening if stored below recommended storage temperature (Reyes and Paull, 1995). The storage at 8–10 °C for more than 3 weeks can enhance the incidence and severity of CI in guava (Singh and Pal, 2008a; Singh and Pal, 2008b; Singh and Pal, 2009). There is potential for shipment of guava in refrigerated containers under CA for long-distance transportation. The atmospheres containing 5–8 kPa O_2 and 2.5–5 kPa CO_2 have been suggested to be optimal for 30 days storage at 8 °C for some commercial cultivars in India (Singh and Pal, 2008a). CA storage may also alleviate CI symptoms in guava fruit. The pre-shipment treatment with 1-MCP can potentially increase the storage and shipping potential of fruit. Sea-freight has been successful for some tropical fruits like mango and banana, but its full potential has not been fully exploited for guava fruit.

10.10 Processing

10.10.1 Fresh-cut

There is an increasing demand for convenient and fresh-cut or ready-to-eat products. The fresh-cut fruit industry faces several challenges such as high perishability, wounding-induced respiration and ethylene production, susceptibility to browning of cut-surfaces, tissue softening, weight loss, changes in flavour and microbial safety issues (Hodges and Toivonen, 2008 and references therein). The deterioration of flavour in fresh-cut products is faster than the loss of appearance, as the physical stress imposed during processing causes losses of major flavour-related volatiles, and synthesis of stress related off-flavour volatiles (Hodges and Toivonen, 2008). Fresh-cut guava can be either a single product or a constituent of mixed fruit salads. The shelf-life and flavour of fresh-cut fruit depends on maturity and fruit quality at harvest. From a sensory rating perspective, 'Kumagai' and 'Paluma' guava harvested at light-green and yellowish-green skin colour stages were found more suitable for fresh-cut processing than those harvested at

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green stage; however, tissue softening and flesh browning were greater in products prepared from fruit harvested at the advanced stages of maturity (Pinto *et al.*, 2009). Generally, the industry prefers firmer and less mature fruits for better shelf-life of fresh-cut products, but sensory ratings of these products are generally inferior to those processed at more mature or ripe stages as reported for guava. It is therefore important to maintain a balance between shelf-life and flavour quality of the fresh-cut product.

The operational steps in fresh-cut guava include washing of fruit, disinfection by immersing in sodium hypochlorite solution (150 mg L^{-1} for 5 min), holding at low temperature 10 °C, peeling or not, cutting into halves and removing the seed cavity, immersing halves in aqueous hypochlorite solution (20 mg L^{-1}), draining for 3 min, packaging in polystyrene trays covered with stretchable polyvinyl chloride (PVC) film (0.017 mm thickness) or in polyethylene terephthalate (PET) containers with lids (Neoform N-94®) (Durigan *et al.*, 2005). PET containers and polystyrene trays covered with PVC film were effective packages for preserving fresh-cut guava under refrigeration (5 °C and 10 °C). Weight loss and changes in peel colour in fresh-cut guava can be delayed by coating with either chitosan (0.2 %) or sucrose fatty acid ester (2 %). Both coating materials did not significantly affect respiration rate, fruit firmness, titratable acidity and ascorbic acid concentration, but increased internal CO_2 levels without development of off-flavours (Thommohaway *et al.*, 2007a; Thommohaway *et al.*, 2007b). Fresh-cut guava produced under appropriate conditions can be stored for 7–8 days at 4–5 °C.

Peeling of fruit in fresh-cut guava is optional. Peeling had no effect on weight loss during refrigerated storage. The appearance quality and ascorbic acid concentration were reported to be superior in non-peeled fruit compared to peeled ones (Durigan *et al.*, 2005). Application of calcium chloride ($CaCl_2$) through vacuum infiltration of fresh-cut guava did not increase levels of Ca generally in the tissue, but resulted in accumulation in the superficial layers of fruit as confirmed by radio-isotope labelling (Durigan *et al.*, 2005). A recent study revealed that exposure of fresh-cut guava to shortwave ultraviolet light (UV-C) for 30 minutes caused a significant increase in the concentrations of polyphenols and flavonoids, and antioxidant capacity (ferric reducing/antioxidant power values) of the tissue (Alothman *et al.*, 2009). UV-C is well-known for its antimicrobial properties. The increase in health-promoting substances in guava fruit tissue exposed to UV-C is another advantage that can be exploited to gain dual benefits, but prolonged exposure to UV-C for 30 min decreased the concentration of ascorbic acid (Alothman *et al.*, 2009). The increase in demand for fresh-cut fruits is driven by the increased awareness among consumers of the health benefits and convenience associated with these products. At the same time, the use of certain synthetic chemicals such as chlorine-based disinfectants, antibrowning agents and antimicrobial compounds may also deter the consumers due to potential health hazards from these substances. More research is required to improve the protocol for developing a healthy and safe fresh-cut guava product that can satisfy consumers and fulfil their nutritional needs.

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10.10.2 Other processed products

Among tropical fruits, guava occupies a distinct position in the processing industry due to its unique and strong flavour. Two to three fruiting seasons per year in most of the guava producing countries and year-round fruiting under some growing conditions offer an exceptional opportunity for the processing industry to continuously access the raw material. Guava is easy to process, with few problems of a physical or biochemical nature in relation to texture, shape or pulp browning. Guava fruit are often processed into juices, puree, concentrates, nectar, canned fruit, jam, jelly, fruit bars and dehydrated powder.

Guava puree is a very important commercial product in the processed products trade. It is commonly used for the preparation of juices, jam, jelly, nectar, syrups and other beverages. The product is obtained by processing sound, mature guava that have been ripened to optimum flavour. The preparation of puree from unripe guava causes problems of astringency, browning and low viscosity. Therefore, fruit maturity plays a crucial role in the final quality of this product. The fruit of the 'Vietnamese' cultivar picked at light green stage changed to yellow-green after exposure to 1000 ppm ethylene for 1.5 days and were the most suitable for processing into puree in comparison with light yellow and bright yellow fruit which were exposed to ethylene for 2.5 and 3 days, respectively (Yusof *et al.*, 1988). Guava fruit should be ripe to have optimum texture, low tannin content and higher soluble pectin for the best quality puree. The high viscosity and cloudy appearance are the special properties of guava puree that may change during thermal processing and storage, thus resulting in quality loss (Yen and Song, 1998). Protein is the major component of clouding substances and is the controlling factor in the degree of cloudiness in guava puree. The processing temperature has marked effects on the protein content and cloudiness of purees. The final product quality is therefore dependent on the raw material and processing techniques used in its production.

Guava juices may be prepared from fresh fruit, puree, concentrate and dehydrated powder. Both clarified and cloudy juices are currently produced from guava and have great market potential (Chopda and Barrett, 2001). Most of the tropical fruit juices are cloudy, but a clear juice is preferred by some consumers. Juices whose turbidity is considered muddy tend to be marketed as clear juices (Brasil *et al.*, 1995). However, Chopda and Barrett (2001) found that sensory panellists preferred cloudy guava juice because they perceived it as a more natural product. Guava juice blends well with other fruit juices. A clarified guava juice can be used in the production of guava nectar, jelly or in various juice blends. Guava juices can also be prepared from puree. The treatment of guava puree with 700 ppm of Pectinex Ultra SP-L® for 1.5 h at 50 °C resulted in a 51% reduction in viscosity, 13% increase in ascorbic acid content and 18% increase in yield of a clearer juice (Chopda and Barrett, 2001). Cloudy or clarified guava nectar is a very popular product in the market and can be prepared from puree or juice.

The flavour and nutritional quality of guava juice is strongly influenced by the processing method. For instance, high pressure processing (25 °C, 600 MPa, 15 min) of guava juice maintained a volatile component profile similar to that of

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the fresh juice during 30 days of storage at 4 °C, while heat processing (95 °C, 5 min) caused decreases in the majority of flavour components in the juice (Yen and Lin, 1999). The pasteurization of guava juice causes 30–45 % losses of ascorbic acid. The absence of oxygen during heat treatment of guava juice can remarkably increase the retention of ascorbic acid. Fresh guava juice subjected to a combination of carbonation and sonication increased ascorbic acid content, but these processes did not have a strong lethal effects on microorganisms (Cheng *et al.*, 2007). In future, coupling of these processes with high pressure or heat can broaden the scope of their application in the guava juice processing industry.

Guava juice concentrates are prepared from clarified or cloudy guava juices and puree. The concentrates are convenient for long-term storage and shipment. The concentration of clarified guava juice using a falling film evaporator increased the SSC by 4.7-fold (42 °Brix), acidity by 3.9-fold (2.05 %) and ascorbic acid 4.2-fold (552.4 mg %). Concentration by falling film evaporator reduces the losses of ascorbic acid compared to other heating methods (Chopda and Barrett, 2001).

Guava juice can be converted into powder to further enhance its commercialization. The best quality guava powder can be produced by freeze drying, which helps retention of ascorbic acid, whereas spray drying is the best method to produce a stable powder with a minimum moisture content of 3 % (Chopda and Barrett, 2001). Because freeze drying is an expensive method to apply commercially and yields hygroscopic powder, spray drying may be the best alternative for producing guava powder. Guava powder can be used to prepare cloudy juices because there was no significant difference in the sensory rating for juices prepared from pasteurized, clear nectar, freeze-dried puree powder and freeze-dried clear juice powder. There is also potential for use of guava powder in formulated drinks, baby foods and other products (Chopda and Barrett, 2001).

Guava are also canned whole, or in slices, halves, and shells in syrup. The development of other guava products such as fruit leather, bars, and wine is also practised on a small scale. The waste from the guava processing industry can be used as a substrate for production of natural food additives. The guava seed meal from the processing waste can be further utilized for oil extraction and as a constituent in other food products. Guava seed meal contains about 10% fat and is rich in linoleic acid, an essential fatty acid (Shams El-Din and Yassen, 1997). Seed oil can be used in salad dressings and for other edible purposes. Food-grade pectin can also be manufactured from guava as they are rich in pectin. Overripe and spoiled fruit may be used for ethanol production.

10.11 Conclusions

The demand for guava is increasing in the world market for fresh and processing purposes. The breeding efforts in several countries have provided cultivars suitable for dessert and processing. Guava fruit offer diversity in shape, skin and flesh colour, and flavour to the consumer. The medicinal properties of different

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parts of the guava tree including fruit have been known to humans since ancient times. Guava fruit is a rich source of vitamins, minerals, fibre and dietary antioxidants. Moreover, health conscious consumers are attracted to the antioxidant-rich products and guava could be one of the best options for antioxidant fibre intake. To meet or preferably exceed consumer expectations, fruit quality must be assured for a sustainable market. Short shelf-life and susceptibility to physical injury, CI and diseases are the major constraints in postharvest handling and storage of guava fruit. Cold storage at 8–10 °C is recommended to maintain fruit quality for 2–3 weeks. Prolonged storage at optimum conditions can promote CI. The response of guava to short-term MA and static CA conditions is favourable and thus marine transport of guava in refrigerated CA containers may be undertaken in the near future. MAP of fruit using films of appropriate thickness has the potential to increase its shelf-life and maintain quality, and should be encouraged for commercial scale adoption in developing countries providing that storage temperatures are carefully controlled. Fruit ripening and senescence can be successfully controlled with postharvest application of 1-MCP.

The fruit growing and postharvest handling conditions in the tropics favour the proliferation of primary and secondary pathogens. As a consequence, fruit rots are common and are mainly controlled by chemical treatments. Furthermore, guava is a universal host of most species of fruit flies, which are among the highly invasive pests across the globe. Therefore, guava fruit must be subjected to phytosanitary treatments to prevent introduction of prohibited pests to importing countries. Such regulatory requirements impede the international trade of fruit. The poor tolerance of guava to temperature-based phytosanitary treatments further adds to the complexity. Gamma-irradiation is an approved and suitable technology for achieving phytosanitation in guava fruit. The scope of guava production for the processing industry is tremendous. The development of fresh-cut guava can increase the options for consumers to eat it in a convenient way. The fresh-cut guava is stable for 7–8 days in refrigerated conditions. Guava juices, nectars and blends with other juices are already popular products in the market. The techniques and protocols have been developed to utilize the waste from guava processing industries.

There is currently a huge gap in the existing postharvest technologies and their adoption in most of the developing countries. The adoption of a postharvest technology will mainly depend upon the return-on-investment factor. Promising technologies such as 1-MCP, irradiation and CA storage are not widely used. A large capital investment in the implementation and operation of CA and irradiation facilities is required, especially in developing countries which contribute greatly to the world production of guava. There is a huge potential for the expansion of the fresh and processing guava industries in the near future.

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Plate XVIII (Chapter 10) Transverse section of a white-fleshed guava fruit.

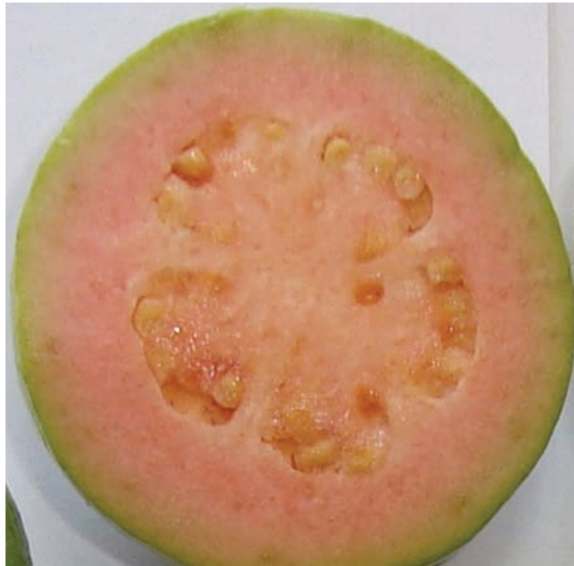

Plate XIX (Chapter 10) Transverse section of a salmon to pink-fleshed guava fruit.

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11

Jaboticaba (*Myrciaria cauliflora* (Mart.) O.Berg. [Myrtaceae])

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Abstract: Jaboticaba is a small tree, native to the central-south of Brazil. Among the well-known species the most important are the *Myrciaria cauliflora* (DC) Berg and the *Myrciaria jaboticaba* (Vell) Berg which produce adequate fruit for both industry (jams, preserves, liqueur and wine) and fresh consumption. This chapter presents the origin, botany, morphology, structure, nutritional value and health benefits of this fruit. It then reviews its postharvest physiology, maturity and quality components, as well as preharvest and postharvest factors which affect fruit quality, problems with physiological and pathological disorders and pests. It also discusses postharvest handling practices and processing.

Key words: *Myrciaria jaboticaba*, phytochemistry, antioxidant, postharvest, processing.

11.1 Introduction

11.1.1 Origin, botany, morphology and structure

Brazil, due to its continental area from Amazonia to its southern region, with ecological conditions that vary greatly from the equatorial and tropical to subtropical, has an immense germplasm resource (Donadio, 1995). Giacometti (1993) proposed ten centers of diversity in Brazil (Fig. 11.1). The Amazonian region is the most important, containing five of them, although all these centers are important areas of origin and domestication of fruit plant species (Donadio, 1995). The south and southeast centers with a subtropical climate are largely different from the others with a predominance of Myrtaceae with more than 50 species of this family (Mattos, 1983). The genera *Eugenia*, *Compomanesia*, *Psidium*, *Hesachlamys* and *Myrciaria* are represented by several species and *Myrciaria jaboticaba* is one of the most important.

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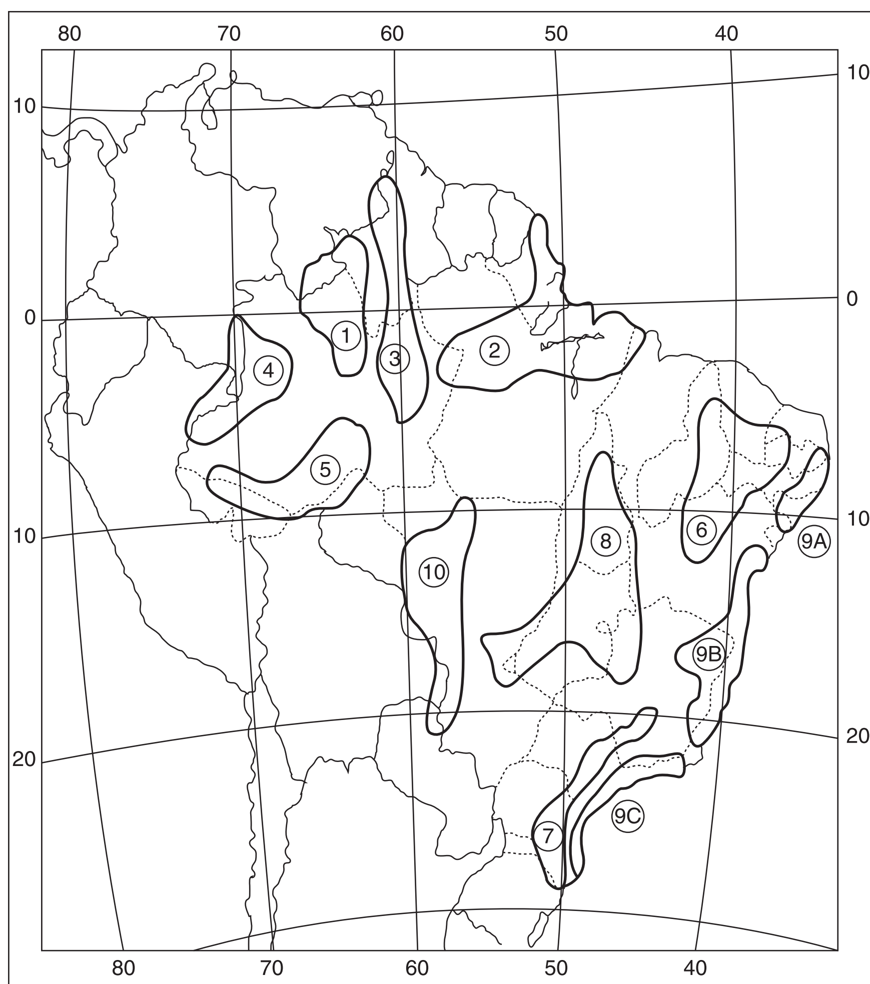

Fig. 11.1 Brazilian centers of diversity for native fruits. 1, High NW/Rio Negro; 2, Atlantic coast/low Amazonia; 3, Manaus/Roraima; 4, Amazonia W/Solimões; 5, Southeast Amazonia/Rondonia; 6, Northeast/Caatinga; 7, South/Southeast; 8, Central Brazil/Cerrado; 9, Atlantic Forest; 9A – Northeast; 9B, Bahia/Espírito Santo/Rio Doce; 9C, Rio de Janeiro/Rio Grande do Sul; 10, Brazil/Paraguay (from: Giacometti (1993)).

The jaboticaba trees (*Myrciaria jaboticaba*) are evergreen plants, mesophilic or heliophilic, found in the Atlantic rainforest and in the altitude sub-forests, in a band that originally stretched from Rio Grande do Sul state to Bahia state, reaching as far as the western states of Goiás and Mato Grosso (Lorenzi, 2002). According to Gomes (1980), the species is rustic and lives in various soil types but grows best in deep, wet silicate clay soil, tolerating temperatures up to −3 °C, but preferring the mesothermal climate.

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Thanks to these features, currently jaboticaba trees are successfully grown in Bolivia, Paraguay, Uruguay, Peru and northern Argentina. In the United States, where jaboticabas were introduced in 1904, plants are grown in regions where winter temperatures are not too low, such as in Florida, Hawaii and California, as well as in Mexico and Central American countries like Honduras and Costa Rica (Duarte *et al.*, 1997).

The name jaboticaba is said to have been given by the Brazilian aboriginals. The Tupis used to eat the fruit either fresh or fermented and they called it *iapati'kaba*, which means 'fruit bud', or *jabotin*, for turtle, and means 'like turtle fat', presumably referring to the fruit pulp (Morton, 1987).

The Myrtaceae family includes about 130 genera and 4600 species of trees or shrubs (Mabberley, 1997). Most are tropical species native to the Americas, Asia, and Australia. Various species have been cultivated, mainly for their fruits. In South America, jaboticaba (*Myrciaria cauliflora*) has been known for more than 400 years.

The Brazilian Myrtaceaes belong to the Myrteae order, forming a phylogenetically cohesive group (Wilson *et al.*, 2001). Based on embryo structure, Candolle (1826) divided the Myrteae tribe into three groups. Berg (1855; 1856a; 1856b; 1857; 1858; 1859) considered the Candolle groups as sub orders: Myrciinae O. Berg, Myrtinae O. Berg and Eugeniinae O. Berg.

According to Mattos (1983), the fruits of the genus *Myrciaria*, called jaboticaba, belong to various species mostly found in Brazil, Paraguay and Argentina (Table 11.1). However, even in the literature there is some confusion about the jaboticaba classification. Mendonça (2000) classified *Myrciaria cauliflora* (Mart.) O. Berg. from a collection belonging to Viçosa, Minas Gerais state, as cultivar 'Açú' and *Myrciaria jaboticaba* (Vell.) O. Berg as 'Sabará'. On the other hand, Pio Corrêa (1969), in the classic dictionary of Brazilian useful plants, has classified *Myrciaria jaboticaba* as cultivar 'Açú' and *Myrciaria trunciflora* O. Berg. as cultivar 'Sabará'. According to Silveira et al. (2006), both species can be distinguished based on the chromosome number, 2n = 48 and 2n = 22, for *Myrciaria trunciflora* and *Myrciaria jaboticaba*, respectively.

Table 11.1 Main jaboticaba species, their common names and origins

Species	Common names	Origin, occurrence
Myrciaria coronata Mattos	Coroada de coroa	São Paulo
Myrciaria olongata Mattos	Azeda	São Paulo
M. spirito santesis Mattos	—	Espírito Santo
Myrciaria grandufolia Mattos	Jabuticatuba graúda	Minas Gerais
Myrciaria peruviana (Poir.)	J.de cabinho	Brazil, Paraguay, Argentina
Myrciaria aureana Mattos	Branca	São Paulo
M. phitrantha (Kiaersk) Mattos	Costada	São Paulo
M. jaboticaba (Vell) Berg	Sabará	Brazil, Paraguay, Argentina
Myrciaria jaboticaba (DC) Berg	Paulista, Assu or Ponhema	Brazil

Source: Mattos (1983)

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Using random amplification of polymorphic DNA (RAPD) markers *Myrciaria coronata* and a plant from the genus *Psidium* spp, initially identified as *Myrciaria*, formed distinct groups and were genetically distant from *Myrciaria jaboticaba* and *Myrciaria cauliflora* (Fig. 11.2). However, these markers did not allow the grouping of plants at the species level, but made it possible to analyze the degrees of genetic similarity among them (Pereira *et al.*, 2005).

Among the well-known species the most important are the *Myrciaria cauliflora* (DC) Berg (jaboticaba 'Paulista' or jaboticaba 'Açú') and the *Myrciaria jaboticaba*

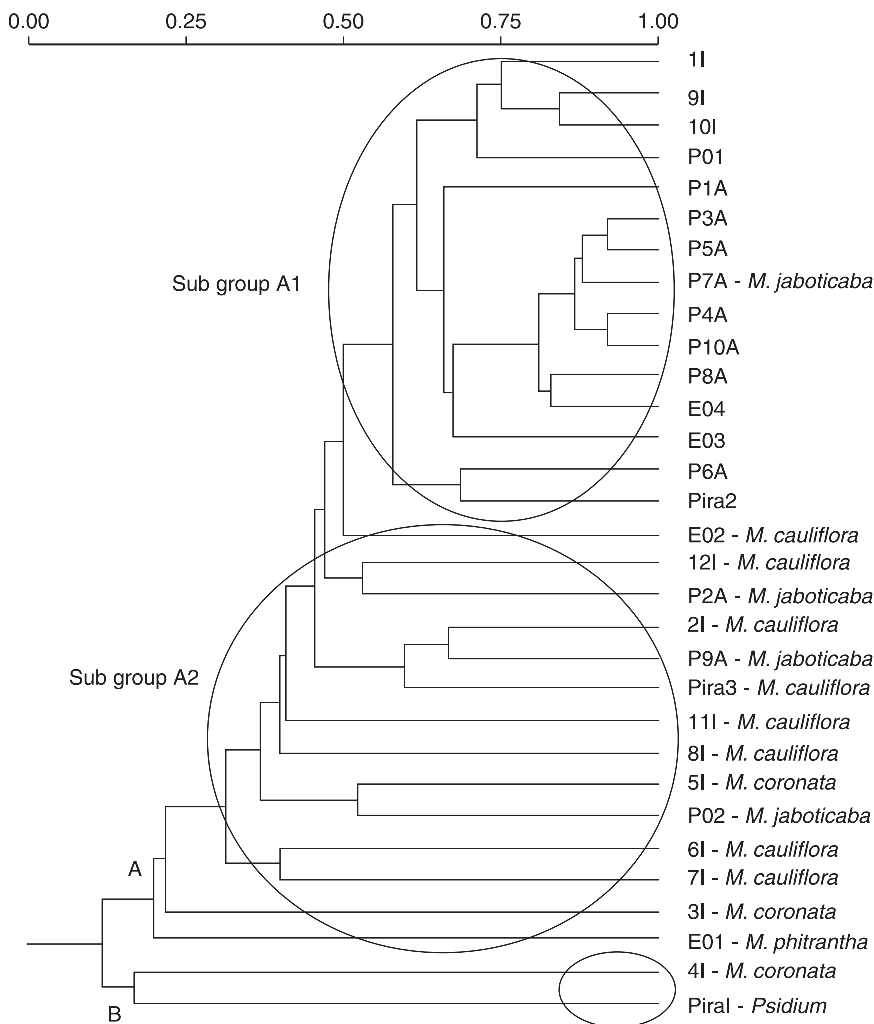

Fig. 11.2 Genetic similarity pattern obtained for 31 'jaboticaba' tree individuals. UPGMA clustering based on the Jaccard similarity index (from: Pereira *et al.* (2005)).

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(Vell) Berg (jaboticaba 'Sabará') which bear adequate fruit for both industry and fresh consumption due to their quality characteristics (Mattos, 1983; Donadio, 1983).

The jaboticaba are slow-growing trees that usually reach 6 to 9 m height, but the shrubby *Myrciaria tenella* reaches just 1.0 to 1.4 m and *Myrciaria trunciflora* may attain 4 to 7 m or rarely 12 m. Trees are profusely branched, beginning close to the ground and slanting upward and outward so that the dense, rounded crown may attain an ultimate spread of 13.7 m (see Plate XX in the color section between pages 274 and 275). However, the tree may grow to considerable size in the deep, fertile soil of its native habitat in Brazil, up to 10.5 to 12 m in height (Mattos, 1983). The thin outer bark, like that of the guava (*Psidium guajava* L.), flakes off, leaving light patches (Morton, 1987).

The leaves are evergreen, opposite, on very short, downy petioles. The limb is lanceolate or elliptic, rounded at the base, sharply or bluntly pointed at the apex; 25 to 40 mm long, 12.5 to 20 mm in width, leathery, dark-green, and glossy.

Spectacularly emerging from the multiple trunks and branches in groups of four (Fig. 11.3), on very short, thick pedicels, the flowers have four hairy, white petals and about 60 stamens up to 4 mm long (Morton, 1987).

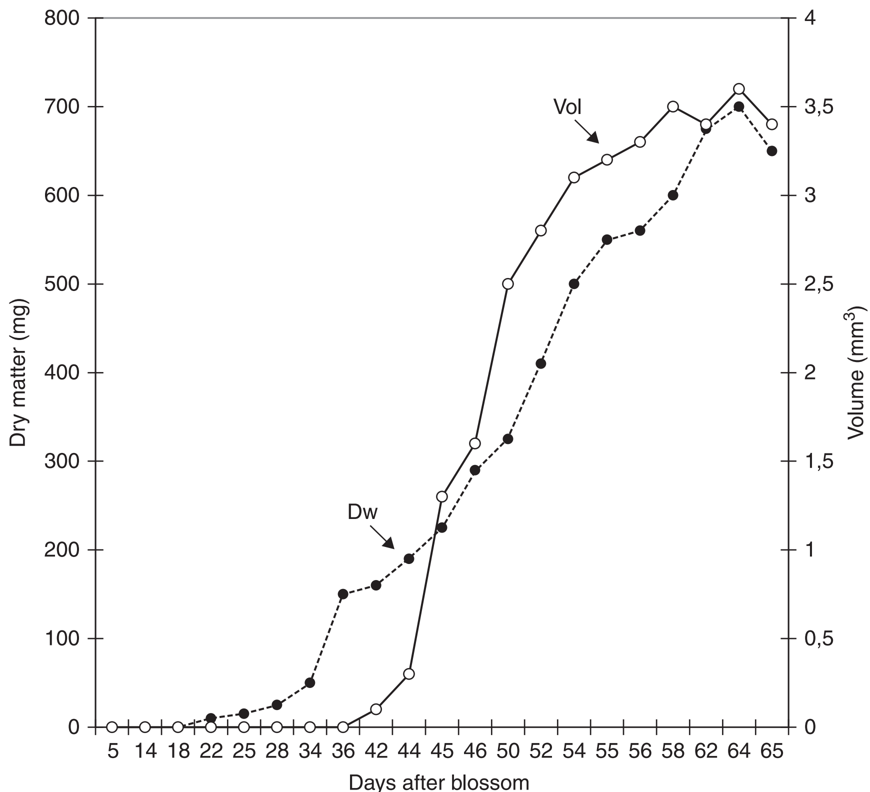

Fig. 11.3 Dry matter accumulation, volume change in fruits of the *Myrciaria jabuticaba* (Vell) Berg 'Sabará' (source: Barros *et al.*, 1996).

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Pereira *et al.* (2005) studying the species *Myrciaria jaboticaba* (Vell.) O. Berg observed the presence of bicarpel ovary, infra-axillary placentation, pilose on the base, style rising above the stamens, captured stigma, numerous stamens, flat terminal branches, green superior and light green lower leaf surfaces, pentamerous actinomorphe corolla and globular 1.6 to 2.2 cm diameter fruits, with smooth and black surface when ripe, containing one to four seeds. These characteristics were in agreement with the descriptions of Mattos (1983).

Pereira *et al.* (2005), studying the species *Myrciaria cauliflora* (Mart.) O. Berg, reported the presence of bicarpel ovary, infra-axillary placentation, glabrous, 6 mm length style, peltate stigma, flat terminal branches and leaf central veins slightly engraved in the higher leaf surface and prominent in the lower leaf surface, pentamerous actinomorphe corolla, glabrous floral buds, 2.2 to 2.8 cm length and 2.2 to 2.9 cm diameter globular fruits.

The fruit of *Myrciaria jaboticaba* (Vell.) O. Berg are globose berries with whitish and juicy pulp, with slightly acid and very sweet flavor, generally 3 to 4 cm in diameter with one to four large seeds, borne directly on the main trunks and branches of the plant, lending a distinctive appearance to the fruiting tree. It has a thick, purple, astringent skin that covers the pulp (Magalhães *et al.*, 1996). The pulp yield varied greatly from 23 to 38% (Table 11.2) depending on the jaboticaba tree source (Jesus *et al.*, 2004).

Table 11.2 Morphological aspects of jabuticabeira fruits [*Myrciaria jaboticaba* (Vell) Berg]

Groups	Weight (g)	Shell (%)	Seed (%)	Pulp (%)	Seed (number)	Length (cm)	Width (cm)
JAB 01	4.5	46	31	23	3.1	1.78	1.53
JAB 02	4.3	33	37	30	2.2	1.58	1.64
JAB 03	3.7	36	35	29	2.2	1.60	1.57
JAB 04	1.6	49	13	38	1.5	1.30	1.21
Média	3.5	41	29	30	2.2	1.49	1.57
SD (%)	24.1	11.5	17.4	16.2	15.9	8.2	9.6

Notes: JAB 01: ovoid crown; JAB 02: spherical with branches crown; JAB 03: compact branches crown; JAB 04: umbrella-like crown.

Source: Jesus *et al.* (2004).

11.1.2 Worldwide importance and economic value

In Brazil most jaboticaba production occurs in its own area of distribution, and the state of Minas Gerais is the largest producer, followed by the states of Paraná, Rio Grande do Sul, São Paulo and Goiás. According to information from IBGE (2006), Brazil's production is still regional, which makes its evaluation very variable and imprecise.

In São Paulo state there are 204 farms producing jaboticaba in an area of 269.80 hectares (São Paulo, 2008). According to Donadio (2000), the total volume

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of jaboticabas traded at the major wholesale market of São Paulo state (CEAGESP) in 1989 was 921 524 kg, which increased to 4 142 047 kg in 1998. In 2008 10 tons were traded (São Paulo, 2008).

In the US jaboticaba is classified as a tropical specialty fruit and distinguished from longan, litchi, mango, rambutan and starfruit (USDA, 2004). In 2003, the Hawaiian production of this category of fruits was 63 957 kg in an area of around 190 hectares with a value of 212 000 U.S. dollars. In 2008, this production increased to 149 688 kg from 220 hectares, with a value of 528 000 U.S. dollars (USDA, 2009).

Balerdi *et al.* (2006) reported that the expected maximum price paid to growers in Florida should be US$ 4.00 to US$ 5.00 per pound (452 g), but commented that buyers may not be able to afford US$ 5.00 per pound.

11.1.3 Culinary uses, nutritional value and health benefits

Jaboticabas are largely eaten fresh in Brazil. Their popularity has been compared to that of grapes in the US. According to Morton (1987), jaboticabas are mostly eaten raw in South America. Traditionally the fruit is eaten by squeezing it between the thumb and forefinger, causing the skin to split and the pulp to slip into the mouth. Morton (1987) also reported that plant explorers Dorsett, Shamel and Popenoe wrote that children in Brazil spend hours 'searching out and devouring the ripe fruits'. It is noteworthy that the seeds are swallowed with the pulp, but the seeds should be discarded as they can cause constipation.

As fresh fruit may begin to ferment within three to four days after harvest, they are often used to make jams, tarts, strong wines and liqueurs. Lima *et al.* (2008) also reported that jaboticaba fruits can be used to produce wines, preserves, jams, juice, acetic and alcoholic fermented goods and liqueurs. They can be preserved by freezing (Balerdi *et al.*, 2006).

The edible flesh (Table 11.3) is about 23 to 38% (Jesus *et al.*, 2004), and contains 79.63% water, 4.0% protein, 4.83% carbohydrate, 2.68% fat (Donadio, 2000; Oliveira *et al.*, 2003; Leterme *et al.*, 2006). According to TACO (2006), a portion of 100 g of jaboticaba contains 58 kcal, 2.3 g of fiber and 0.06 mg of thiamine. The pulp is rich in vitamin C containing about 23 mg 100 g^{-1} (Purdue, 2000) and minerals, mainly potassium and calcium (Leung and Flores, 1961; Leterme *et al.*, 2006; TACO, 2006).

Recent studies have shown that many flavonoids and related polyphenols contribute significantly to the total antioxidant activity of many fruits and vegetables (Vinson *et al.*, 1999; Luo *et al.*, 2002). Anthocyanins are a group of well-studied phenolic compounds with antioxidant, anti-inflammatory, antimutagenic and cancer chemopreventative activities (Einbond *et al.*, 2004). The jaboticaba has been reported to contain tannins (Morton, 1987). Einbond *et al.* (2004) reported the presence of cyanidin 3-glucoside in *Myrciaria cauliflora*. According to Trevisan *et al.* (1972), *Myrciaria jaboticaba* contains peonidin 3-glucoside and its aglycone as anthocyanin compounds. Zanatta *et al.* (2005) studying the antioxidants and cancer chemopreventative compounds from tropical

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Table 11.3 Chemical composition of jaboticaba [*Myrciaria jaboticaba* (Vell) Berg]

Components	Values
Water (%)	79.63
Dry matter (%)	20.37
Titratable acidity (%)	1.25
Soluble solids (°Brix)	14.36
pH	3.49
Ratio SS/AT	13.14
Ascorbic acid (mg 100 g^{-1})	19.24
Total carbohydrates (%)	4.83
Protein (%)	4.00
Fat (%)	2.68
Fibre (%)	4.52
Ash (%)	4.79
Calcium (mg 100 g^{-1})	50
Phosphorus (mg 100 g^{-1})	14
Potassium (mg 100 g^{-1})	371
Magnesium (mg 100 g^{-1})	15
Sulphur (mg 100 g^{-1})	8
Sodium (mg 100 g^{-1})	3
Chloride (mg 100 g^{-1})	46
Copper (mg 100 g^{-1})	0.06
Iron (mg 100 g^{-1})	0.33
Manganese (mg 100 g^{-1})	0.28
Zinc (mg 100 g^{-1})	0.19
Selenium (mg 100 g^{-1})	nd
Cobalt (mg 100 g^{-1})	nd
Nickel (mg 100 g^{-1})	0.03
Chromium (mg 100 g^{-1})	nd

Sources: Donadio (2000); Oliveira *et al.* (2003); Leterme *et al.* (2006).

fruits, found in jaboticaba crude methanolic extracts strong antiradical activity in the 1,1-diphenyl-2-picrylhydrazyl (DPPH) antiradical assay (IC_{50} 35 μg mL^{-1}). Fruit extracts subsequently subjected to bioactivity-guided fractionation using the DPPH assay, resulted in the isolation of a new depside (phenolic compounds composed of two or more monocyclic aromatic units linked by an ester bond), 'jaboticabin' (Reynertson *et al.*, 2006). In addition, the related depside 2-*O*-(3,4-dihydroxybenzoyl)-2,4,6-trihydroxyphenylacetic acid (Popenoe, 1920; Einbond *et al.*, 2004), pyranocyanin B, quercetin, isoquercitrin, quercimeritrin, quercitrin, rutin, myricitrin, cinnamic acid, *O*-coumaric acid, gallic acid, protocatechuic acid, methyl protocatechuate and ellagic acid were identified from this species for the first time (Reynertson *et al.*, 2006).

According to Reynertson *et al.* (2008), the antiradical activity of *Myrciaria cauliflora* is very high (19.4 μg mL^{-1}) and it was the most active extract in the DPPH assay compared to 14 underutilized Myrtaceae fruits, with jaboticaba

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Table 11.4 Common phenolics in jaboticaba [*Myrciaria cauliflora* (Vell) Berg]

Compounds	Values (mg g^{-1})
Cyanidin 3-glc	4.33
Delphinidin 3-glc	0.81
Ellagic acid	0.52
Myricetin	0.02
Quercetin	0.04
Quercetrin	0.11
Rutin	0.21

Source: Reynertson *et al.* (2008)

presenting only a slightly higher total phenolic content (TPC), 31.6 mg g^{-1}, and total anthocyanin content (TAC), 2.78 mg g^{-1}. These authors also reported the presence of cyaniding 3-glucoside, depphinidin 3-glucoside, ellagic acid, myricetin, quercitin, quercitrin and rutin (Table 11.4).

The astringent decoction of the sun-dried skins is prescribed in Brazil as a treatment for hemoptysis, asthma, diarrhea and dysentery; also as a gargle for chronic inflammation of the tonsils (Morton, 1987), most probably due to the tannin content.

11.2 Fruit development and postharvest physiology

11.2.1 Fruit growth, development and maturation

Intense vegetative growth occurs at the end of winter and beginning of spring, before the main bloom season, with blossoms emerging from the trunks and branches (Figure 11.3). According to Duarte (2003a), the reproductive behavior of the jaboticaba tree indicates that the thicker the branch the greater the occurrence of flowers and fruits, and the quantity of fruits may vary from 30 to 400 per meter of branch.

Regarding the reproduction process, each flower produces a great quantity of pollen which remain available for pollination and fertilization, even though the style is receptive since the blossom opening. It permits self- and cross-pollination. The percentage of fertilization varies from 7 to 30%, and this index can be increased to 60 to 70% under protected conditions (Duarte, 2003b).

In ideal climatic and cultivation conditions up to five blooms can occur in a year (Duarte, 2003a,b). According to Mattos (1993), in Brazil the fruiting season varies according to the species and place, e.g., in *Myrciaria cauliflora*, it can happen from September to January in São Paulo state. On the other hand, in *Myrciaria grandiflora* and *Myrciaria peruviana* var *trunciflora*, fruiting occurs from March to September in Paraná state.

Jaboticaba presents a simple sigmoid growth pattern of development (Fig. 11.4). Duarte (1995) and Magalhães (1991) reported that fruits of *Myrciaria cauliflora* grow

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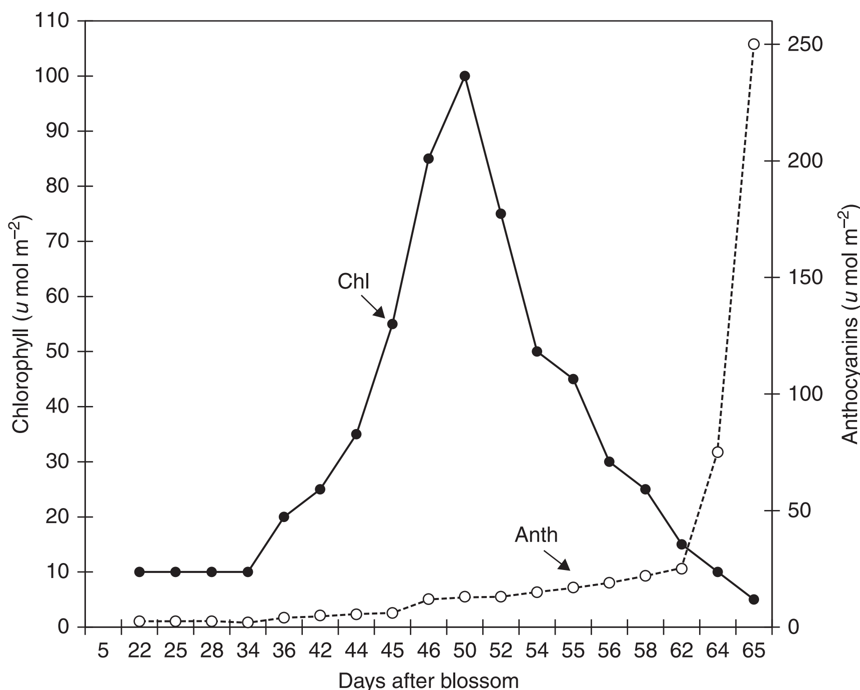

Fig. 11.4 Pigment content in fruits of the *Myrciaria jabuticaba* (Vell) Berg 'Sabará' (redrawn from Barros *et al.*, 1996).

slowly for the 12 first days after blossom. After this period the growth is rapid, leading the fruit to increase from 2 g to 4 g in 20 days, maintaining the growth until 28 days, when there is a period of stability until the thirtieth day after bloom.

Magalhães (1991) reported that the first phase of development is marked by slow growth, and after the 25th day after anthesis (DAA) this growth is accelerated and rapid expansion of cell volume occurs, due to high water absorption. At 57 DAA stabilization occurs in the growth of fruits, while loss of chlorophyll and anthocyanins levels of the skin increase. Fruit development in the plant occurs in approximately 60 days. The final fruit weight is around 5 g (Barros *et al.*, 1996).

11.2.2 Respiration, ethylene production and ripening

Jaboticaba postharvest handling is difficult due to the fragility of the fruit and its highly perishable character, with fruits having an extremely reduced shelf-life of two to three days at room temperature (Donadio, 2000; Cantwell, 2001).

Corrêa (2006) indicated that during the period of fruit development, respiratory activity increased significantly, which was related to the necessity of increased energy production for metabolic processes of maturation.

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The respiration rates soon after harvest are very high, with values ranging from 116.54 mg CO_2 kg^{-1} h^{-1} (Mota *et al.*, 2002) to 159.33 mg CO_2 kg^{-1} h^{-1} (Durigan *et al.*, unpublished data). The climacteric status seems to follow the pattern attributed to non-climacteric fruit, as jaboticabas (*Myrciaria jaboticaba* Berg. 'Sabará') showed a gradual decline in the respiration rate after harvest from 116.54 to 95.54 mg CO_2 kg^{-1} h^{-1} after four days at ambient temperature. However, after six days at ambient temperature the respiration rates increased mainly due to pulp fermentation (Motta *et al.*, 2002).

Corrêa (2006) found a low initial respiration rate, which gradually increases until the 45th DAA, when the fruit reach good quality for consumption that can be related to skin color, which ranges from red to dark red. The typical dark purple color appears around 50 and 55 DAA, when the respiratory activity reaches its maximum values, and in this period the fruit is suitable for consumption and is usually harvested then. Then the respiratory activity begins to decrease, indicating the onset of senescence and on 65 DAA fruit no longer display good quality for consumption and there is a slight increase in respiratory activity typical of advanced senescence.

Respiration rate can be sharply reduced by dipping the fruits in cold water at 15 °C. Oliveira *et al.* (2003) immersed jaboticabas from different sources in cold water and reported a carbon dioxide production rate ranging from 17.76 to 36.17 mg CO_2 kg^{-1} h^{-1}. Durigan *et al.* (unpublished data) also reported a reduced respiration rate when jaboticabas were stored under controlled atmosphere (CA) with different levels of oxygen (O_2) at 12.5 °C. Fruits maintained in atmospheres containing 1% and 5% O_2 had a lower respiration rate (47.71 mg CO_2 kg^{-1} h^{-1}) than those kept in 10%, 15% and 21% O_2 (56.03 mg CO_2 kg^{-1} h^{-1}) for up to nine days at 12.5 °C.

11.3 Maturity and quality components and indices

Maturity of fruits can be determined by size, weight, color, sugar content, acidity, ratio of soluble solids and titratable acidity (SS/AT), aroma and days after blossom (Holcroft and Mitcham, 1996). Commonly, jaboticaba maturity is determined by color, as soluble sugar and acidity vary greatly according to climate conditions (Oliveira *et al.*, 2003).

Barros *et al.* (1996), studying the *Myrciaria jaboticaba*, reported a reduced dry matter accumulation from about 20 days after blossom. Fruit size and volume increase and reach their maximum (Figure 11.4).

During the development of the fruit chlorophyll increases sharply after 30 days after blossom (DAB) and reaches its maximum content around 50 DAB (Fig. 11.5). From this point chlorophyll content declines dramatically and coincides with the synthesis of flavonoids, particularly anthocyanins, which increase during maturation and are responsible for the purple color of the fruits (Magalhães, 1991; Barros *et al.*, 1996). Anthocyanins content soared from around 25 to 250 µmol m^{-2} after 60 DAB (Fig. 11.5). The main anthocyanin

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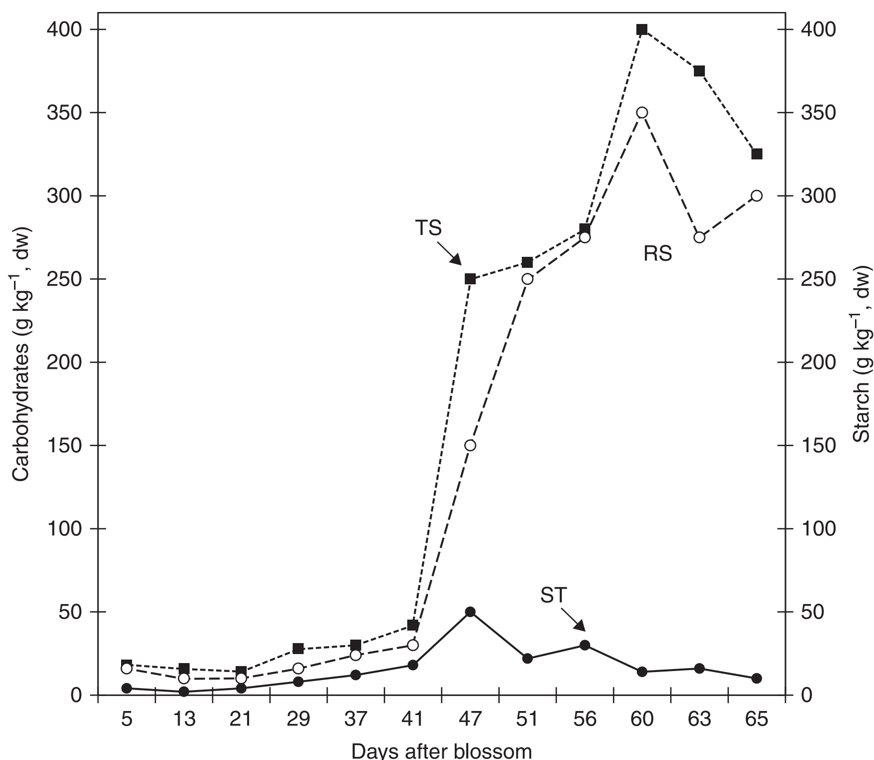

Fig. 11.5 Non-structural carbohydrates content in fruits of the *Myrciaria jabuticaba* (Vell) Berg 'Sabará'. TS, total sugar; RS, reducing sugar; ST, starch (redrawn from Barros *et al.*, 1996).

compounds are cyanidin 3-glucoside and delphinidin 3-glucoside in *Myrciaria cauliflora* (Einbond *et al.*, 2004), pheonidin 3-glucoside and its glycone in *Myrciaria jaboticaba* (Trevisan *et al.*, 1972).

The accumulation of carbohydrates increases slowly from 30 DAB (Fig. 11.6). Substantial increments coincide with a marked increase in volume (Barros *et al.*, 1996; Corrêa, 2006). According to these authors, by 50 DAB fruit size was maximum, but dry matter and soluble sugars continued to accumulate until near the end of fruit development (Fig. 11.6). Starch content reaches its maximum around 45 DAB and decreases afterwards. The decrease in the total amount with formation of soluble sugars (SS) is a significant change in the development of jaboticaba fruit (Magalhães, 1991; Barros *et al.*, 1996). Concentration of sugars at the end of fruit development was associated with the final stages of ripening. This increase in the biosynthesis of polysaccharides is indicated by the increase in SS, which according to Corrêa (2006) ranges from 2.1°Brix at 25 DAA to 18.6°Brix at 52 DAA. After 55 DAA these values reduced, which was also reported by Barros *et al.* (1996).

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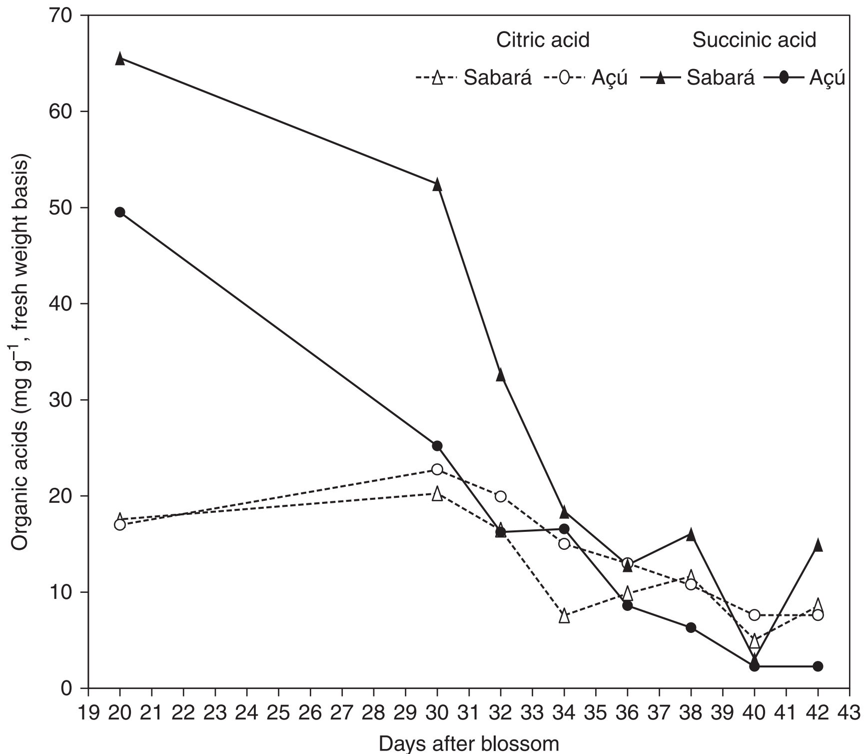

Fig. 11.6 Changes in jaboticaba varieties 'Sabará' and 'Açú' organic acids after flowering (redrawn from Jham *et al.*, 2007).

Organic acids decrease during jaboticaba fruit development (Fig. 11.7). Succinic and citric acids are the main organic acids in jaboticaba 'Sabará' and 'Açú' (Jham *et al.*, 2007). In 'Sabará', the concentration in pulp reached its highest content at 20 DAB, decreased up to 38 DAB and remained steady afterwards. Similar tendency is observed in the pericarp contents in which succinic acid is higher than the corresponding value in the pulp on all days (Fig. 11.7). The same trend is observed for 'Açú' jaboticaba. Citric acid is the second most abundant organic acid (Jhan *et al.*, 2007). In 'Sabará', after an initial rise from 20 DAB, citric acid in the pulp decreases up to 36 DAB. In 'Açú', also after an initial rise from 20 DAB the concentration decreased up to 38 DAB. In the pericarp of both varieties citric acid content was quite random (Fig. 11.7). Malic acid is detected only in trace amounts in both varieties, both in the pulp and pericarp (Jhan *et al.*, 2007).

Corrêa (2006), however, reported that titratable acidity (TA) in jaboticabas increased with fruit development, from 0.2% at 25 DAA to 0.7% of citric acid at 55 DAA, and then decreased to 0.4% up to 60 DAA.

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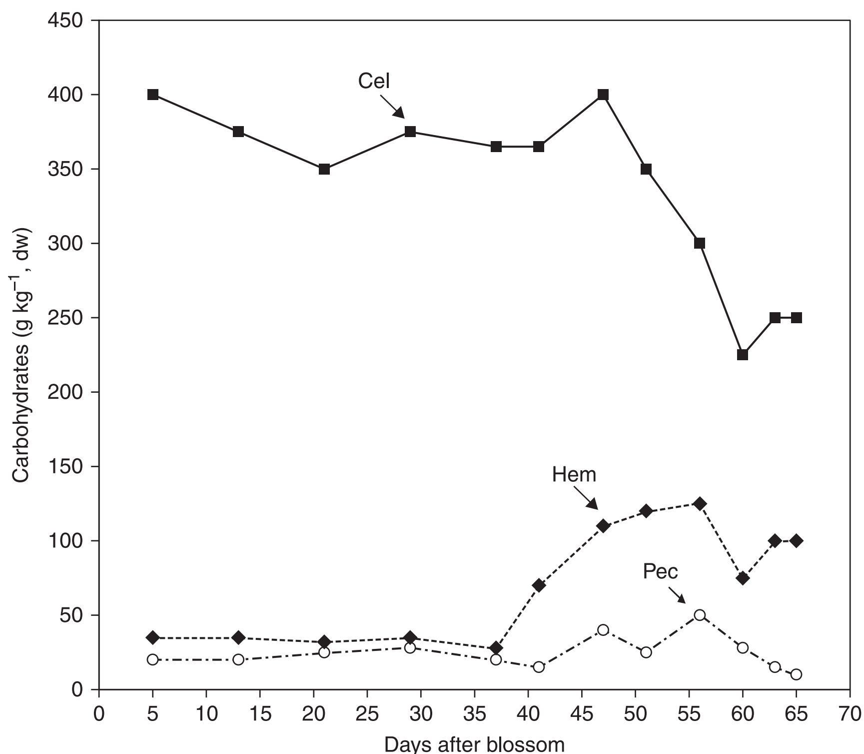

Fig. 11.7 Structural carbohydrates content in fruits of the *Myrciaria jabuticaba* (Vell) Berg 'Sabará'. Cel, cellulose; Hem, hemicellulose; Pec, pectin (redrawn from Magalhães *et al.*, 1996).

Cellulose is the predominant structural carbohydrate of jaboticaba fruit, followed by hemicellulose and pectin (Fig. 11.8). According to Magalhães *et al.* (1996), most of the increase in the content of structural carbohydrates begins about 37 DAB, which coincides with the rapid increase of berry volume and dry matter (Barros *et al.*, 1996). After about 53 DAB, hemicellulose accumulation is relatively stable, but the pectin content decreases dramatically after 55 DAB (Fig. 11.8).

Fruit firmness is reduced continuously during the period of development, which was attributed to a decrease in the levels of hemicellulose (Magalhães *et al.*, 2006) and the intense distribution of sugars in the cells of the fruit (Lima, 2002).

Based on changes in anthocyanins and chlorophyll contents of the berry, ripening of jaboticaba appears to begin at 55 DAB (Figure 11.5). From this stage onwards, the total pectin declines sharply, as also does its content on a dry weight basis (Fig. 11.8). As with many other fruits, partial breakdown of pectin and cellulose occurs during jaboticaba ripening.

As jaboticaba is non-climacteric and does not ripen after harvest, berries should be harvested when appearance and quality are ideal for consumption. In this

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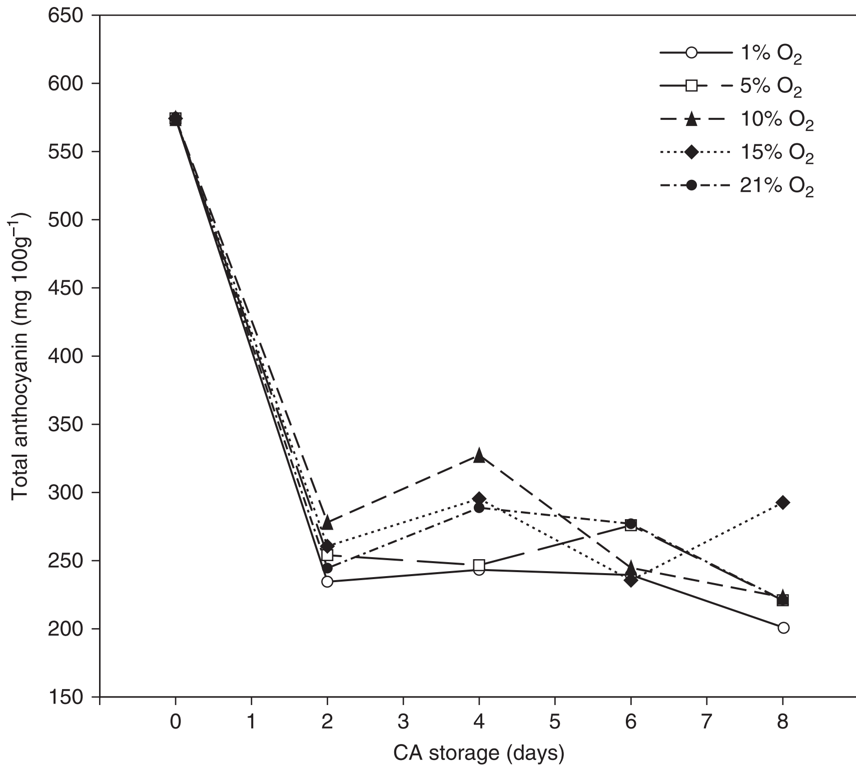

Fig. 11.8 Anthocyanin content in fruits of the *Myrciaria jabuticaba* (Vell) Berg 'Sabará' stored under controlled atmosphere at 12.5°C (source: Durigan *et al.* (unpublished data)).

regard, jaboticabas should be harvest when berries are fully developed and with purple color, as immature fruits are acidic, do not ripen and their flavor will not improve after harvest.

11.4 Preharvest factors affecting fruit quality

The jaboticaba tree usually has a long juvenile period and does not bear fruit for the first eight or more years, but it may fruit in less time under particularly favorable conditions (Balerdi *et al.*, 2006). Production may begin in four to 15 years but usually eight to ten years from seed and about six to seven years from vegetative propagation by grafting, cuttings and air layering (Duarte and Huete, 1996a,b; Wiltbank *et al.*, 1983).

Jaboticaba trees may become large after many years. Close initial in-row spacings of 3 to 3.6 m may be justified because of the slow growth habit of the tree. A minimum of 4.6 to 6.0 m between rows should provide sufficient space for tree development (Balerdi *et al.*, 2006).

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In Brazil, the orchards were mostly formed from jaboticaba seedlings planted from seeds. According to Phillips and Goldweber (2005), *Myrciaria cauliflora* produces apomictic, polyembryonic seeds and all seedlings are identical to the mother tree. On the other hand, *Myrciaria jaboticaba* produces zygotic, monoembryonic seeds with variability in the seedling population. Some references indicate the existence of hybrids between these two species (Wiltbank *et al.*, 1983). Morton (1987) reported that orchards with more than one cultivar or seedling type produce better than those with just one cultivar.

According to Balerdi *et al.* (2006), jaboticabas respond very well to organic matter so the use of compost and manure is recommended. Mulching is also beneficial; use a 10 to 15 cm layer of mulch beginning 20 to 30 cm from the trunk and covering most of the area under the canopy.

Fertilization depends on tree size and the amount increases as trees grow larger. Donadio (2000) reported the input of 30 to 50 kg of cow manure and 250 g of NPK per plant per year. It should be done in frequent applications around the area under the canopy during the rainy season.

Jaboticaba trees are susceptible to drought and should be irrigated regularly during the dry months if it does not rain. Irrigation is important from flowering to harvest.

Light pruning is required to remove dead, damaged and crossed branches. Removal of many of the thin inside shoots is also recommended as fruiting does not occur on heavily shaded branches. Trees should be topped to reduce height to about 3.0 to 3.6 m. Tree size may also be influenced by grafting and growth regulators (Donadio *et al.*, 2002). Dwarf plants have been reported and can also be used in high density plantings (Jesus *et al.*, 2004).

According to Balerdi *et al.* (2006), harvesting is tedious and expensive due to the small size of fruits, which have to be harvested individually on the trunk. Cannon (1999) and Coppens and Libreros (2001) reported this aspect as the major drawback in growing jaboticabas.

11.5 Postharvest handling factors affecting quality

Jaboticaba postharvest handling is difficult due to the fragility of the fruit and its highly perishable characteristic, resulting in extremely reduced shelf-life of two to three days at 24 °C (Duarte *et al.*, 1997; Donadio, 2000; Corrêa, 2002).

11.5.1 Temperature management

Jaboticaba fruits are commonly managed at ambient temperature. As they are very perishable, at warm temperatures fruits soften by the second day and shrivel, and begin to ferment by the third day (Jesus *et al.*, 2004; Duarte *et al.*, 1997; Mootoo and Henry, 1996). Without refrigeration, jaboticabas must reach the market in one or two days (Balerdi *et al.*, 2006).

In an attempt to improve fruit shelf-life, Motta *et al.* (2002) dipped jaboticaba fruits, *Myrciaria jaboticaba* Berg. 'Sabará', in $CaCl_2$ 40 g L^{-1} (w:v) for up to

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60 minutes. However, this treatment had little effect on shelf-life and fruit were considered acceptable only for four days at ambient temperatures.

Refrigeration is very helpful in prolonging the shelf-life of the fruit (Balerdi *et al.*, 2006). Jaboticaba *Myrciaria cauliflora* is a subtropical fruit and should be stored at 13–15 °C and 90–95% relative humidity (RH), with fruit having an approximate shelf-life of three days (Cantwell, 2001). Duarte *et al.* (1997) reported that the best temperature at which to store jaboticabas is 12 °C, as it maintains the fruit quality and extends shelf-life, but Corrêa (2006) recommended 10 °C.

Lower temperatures have been used during jaboticaba storage. Fruits packed in trays of polystyrene covered with polyvinyl chloride film (thickness 0.012–0.030 mm), were considered acceptable after storage for six days at 11 °C and 98% RH (Brunini *et al.*, 2004). Machado *et al.* (2007) extended the shelf-life to eight days when fruits were stored at 0 °C, but shrivelling was the major problem. Refrigeration should be combined with other techniques in order to minimize water loss.

11.5.2 Physical damage

During storage, fruits frequently show a sort of purple watering lesion throughout the pulp/skin interface. There are no reports on this problem, but it is probably due to physical damage to jaboticaba skin, leading the anthocyanins from the epidermal cells on the inner skin to spread into the pulp. This damage probably occurs during harvest as the small fruits must be collected individually from the trunk and branches. However, inadequate sorting and packing practices can also contribute to the problem.

11.5.3 Water loss

During postharvest handling of jaboticaba, fruit water loss is responsible for the intense weight loss and subsequent shrivelling of the berries. Up to 11.25% weight loss can occur in just two days at ambient temperatures, and loss as high as 28.2% was reported in unwrapped fruits after eight days at 0 °C (Machado *et al.*, 2007), reaching up to 47.3% in one week at 24 °C (Duarte *et al.*, 1997).

Water loss is significantly reduced by refrigeration. Brunini *et al.* (2004) reported that unwrapped fruits showed 11.25% weight loss after two days at ambient temperature (26 to 28 °C and 54 to 68% RH). On the other hand, at 11 °C and 98% RH this loss was reduced to 1.20% at the same period and reached 3.05% after four days.

Waxing can potentially reduce water loss during jaboticaba storage. Duarte *et al.* (1997) used Brogdex Tomato Wax no. 590–1, 1:200 (v:v) to treat jaboticaba fruit and reported a control of water loss from 25.6% for fruits stored at room temperature (24 °C) to 2.4% of those stored at 12 °C and 85–90% RH after three weeks. On the other hand, Corrêa (2006) reported weight losses of 27.98% and 25.59% during storage at 10 °C and 8 °C, respectively, and the use of wax (Sta

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Fresh at 2–3% of solids) did not significantly affect water loss, but immersion in gibberellic acid (GA_3) at 200 mg L^{-1} significantly reduced this loss.

When refrigeration is combined with packaging the water loss can be further reduced. Wrapping jaboticabas with low-density polyethylene films (LDPE) of 0.012mm or 0.020 mm thickness reduced water loss to 3.14 to 2.41% and 0.44 to 0.51%, after three and six days in ambient or in cold storage (11 °C), respectively (Brunini *et al.*, 2004). These values were quite similar to those presented by Machado *et al.* (2007), with LDPE film of 0.015 mm reducing weight loss to 3.49% after eight days at 0 °C. Polyethylene bags (0.025 mm thick) also controlled water loss of jaboticaba fruits stored at 6 °C, 12 °C and 24 °C (Duarte *et al.*, 1997).

11.5.4 Atmosphere

Modified atmosphere (MA) can reduce weight loss, shrivelling, development of postharvest decay and softening (Tucker, 1993; Kader, 2003; Chitarra and Chitarra, 2005).

Wrapping and/or the use of small plastic containers such as plastic wrapped strawberry, blueberry/blackberry baskets or clam shells dramatically increase shelf-life with refrigeration and this is the way to pack and store jaboticabas (Balerdi *et al.*, 2006). MA, developed by packing in LDPE films, allowed longer shelf-life of about two weeks without refrigeration and a month with refrigeration (Duarte *et al.*, 1997; Mootoo and Henry, 1996).

Waxing was also tested using an aqueous solution of ‘Brogdex Tomato Wax’, 1:200 (v:v) by Duarte *et al.* (1997). After two weeks at 12 °C the authors rated 80% of the fruits as edible mainly due to reduction of water loss and improvement of the external appearance (gloss).

Corrêa (2006) reported that the use of wax reduced the loss of firmness of jaboticabas stored at 8 °C and 10 °C for 15 days, without affecting the acidity, but slowing the respiratory activity of these fruits, which influenced the peroxidase activity. This author concluded that treatment with wax does not affect the conservation of this fruit, but greatly improves its appearance.

Although some studies have been carried out using MA storage, none of them determined the internal atmosphere composition (Duarte *et al.*, 1997; Mootoo and Henry, 1996; Brunini *et al.*, 2004; Machado *et al.*, 2007).

Durigan *et al.* (unpublished data) reported that controlled atmosphere (CA) storage with different oxygen (O_2) concentration at 12.5 °C did have some effect on jaboticaba quality. When fruits were stored at 1 to 5% O_2 the respiration rate was lower (47.71 mg CO_2 kg^{-1} h^{-1}) than those maintained in 10, 15 and 21% O_2 atmospheres (56.03 mg CO_2 kg^{-1} h^{-1}) for up to nine days at 12.5 °C. On the other hand, firmness was negatively affected by low oxygen levels with fruits stored in 1% O_2 presenting the lower values (0.48 kgf cm^{-2}).

Anthocyanin content was not affected by CA storage either in 21 or 1% O_2 (Fig. 11.8). After just two days anthocyanins were reduced from 547.27 to 254.28 mg 100 g^{-1} and remained quite constant for eight days of storage.

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The main CA effect on quality independently of O_2 concentration was the control of water loss that was as low as 0.79% after eight days at 12.5 °C. It was probably due to the humidified air flow which was used during storage, but, unfortunately, it allowed decay development after eight days of CA storage.

Based on these results, jaboticaba can be stored in an atmosphere containing 5% O_2 and the ethylene level must be kept below 1 mg L^{-1} (Cantwell, 2001).

11.6 Physiological disorders

11.6.1 Chilling injury

Temperatures recommended for jaboticaba storage range from 12 °C (Corrêa, 2006) to 13–15 °C (Duarte *et al.*, 1996; Cantwell, 2001). Machado *et al.* (2007) stored jaboticaba fruits (*Myrciaria* spp) at 0 °C for up to eight days and no chilling injury symptom was mentioned. On the other hand, Duarte *et al.* (1997) reported that chilling injury occurred on jaboticabas after three weeks storage at 6 °C, but no injury description was provided. The absence of chilling injury in the study of Machado *et al.* (2007) might be due to the short storage period (eight days) compared to Duarte *et al.* (1997). This may not allow the development and/or manifestation of this physiological disorder. Corrêa (2006) reported that fruits harvested at 45 DAA and stored at 8 °C for 15 days failed to achieve the dark color typical of ripe fruit.

11.7 Pathological disorders

Some diseases and their causal organisms are specific to certain countries and others are widespread where jaboticabas are grown (Table 11.5). Anthracnose is widespread and is considered an important disease in most countries. Balerdi *et al.* (2006) reported the absence of serious diseases in Florida. However, these authors also stated that anthracnose sometimes has caused severe rotting in jaboticaba.

Rust caused by *Puccinia psidii* Wint. affects leaves, blossoms, flowers, fruits and branches. Round necrotic lesions are covered by vivid yellow powder mass (fungi spores). According to Morton (1987), if blooming occurs during heavy

Table 11.5 Some important diseases of jaboticaba [*Myrciaria cauliflora* (Vell) Berg]

Common name	Organism	Parts affected
Anthracnose	*Colletotrichum gloeosporioides*	Stem, leaf, blossom, fruit
Rust	*Puccinia psidii*	Stem, leaf, blossom, fruit
Dieback	*Rosellinia*	Root
Fruit rots	*Botrytis cinerea*	Fruit

Sources: Morton (1987); Donadio, 2000

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rains, many flowers will be affected by rust. The variety 'Sabará' is particularly susceptible to attacks of rust on the flowers and fruits. Control is possible using Bordeaux mixture or fungicides.

Fungal decay was reported by Duarte *et al.* (1997) during storage. Durigan *et al.* (unpublished data) also observed intensive growth of a white mycelium on the fruit skin after eight days under CA (15% and 21% O_2) storage at 12.5 °C and 95% RH. This decay may develop on either the stem end portion of the fruit or on micro cracks on the skin.

11.8 Insect pests

A number of insect pests have been reported in the literature (Table 11.6). One of the most serious insects is the Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann). Jaboticaba is considered a host fruit of Mediterranean fruit fly, and in this regard requires quarantine treatment for entry to some countries.

In Australia, the state of Queensland, according to the Plant Protection Regulation 2002, which is subordinate legislation to the Plant Protection Act 1989, specifies the requirements for the entry of plants, plant products and other related items that risk introducing plant pests or diseases. Based on the approved treatments, jaboticaba must be treated with methyl bromide fumigation at the rates of 48 mg m^3 for two hours at 10 to 14.9 °C; 40 mg m^3 for two hours at 15 to 20.9 °C; 32 mg m^3 for two hours at 21 to 25.9 °C; and 24 mg m^3 for two hours at 26 to 31.9 °C. Jaboticabas can also be cold treated for at least 14 days at 0.0 + 0.5 °C, 16 days at 1.0 + 0.5 °C, 18 days at 1.5 + 0.5 °C, or 20 days at 2.5 + 0.5 °C. Other treatments such as fenthion dipping or spraying, heat treatments (hot water dipping, high temperature forced air or vapor heat), maturity (green condition) are not recommended for jaboticaba (Queensland Government, 2007).

Table 11.6 Some important pests of jaboticaba [*Myrciaria cauliflora* (Vell) Berg]

Common name	Organism	Parts affected
Mediterranean fruit fly	*Ceratitis capitata*	Fruit
Fruit fly	*Anastrefa fraterculus*, *A. obliqua*	Fruit
Jaboticaba worm	*Conotrachelus myrciariae*	Fruit, seed
Soft scale	*Capulinia jaboticabae*	Stem, leaf, blossom, fruit
Wax scale	*Ceroplastes janeirensis*	Stem, leaf, blossom, fruit
Myrtaceae borer	*Timocrata albella*	Stem
Black citrus aphid	*Toxoptera aurantii*	Stem, leaf, blossom, fruit
Irapuá bee	*Trigonas spinipes*	Fruit
Green bud	*Paraulaca clines*	Stem
Birds		Fruit
Other animals		Fruit

Sources: Morton (1987); Gallo (1988); Donadio (2000)

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Other species of fruit flies such as *Anastrefa fraterculus* and *Anastrefa obliqua* were reported by Gallo (1988) in Brazil. The larvae damage the fruit as they eat the pulp. Interestingly, this author reported that the variety 'Sabará' is not infected by either species, and generally growers do not control fruit fly infestation.

Fruits can be infected by *Conotrachelus myrciariae* (Marshall, 1929), a Coleoptera from the Curculionidae family. The adult bud is yellow and the larva is white without legs, 9 mm long. The larva tunnel into the pulp and also consumes the seeds. Affected fruits must be destroyed and spraying with insecticides is recommended.

A soft scale, *Capulinia jaboticabae*, Homopterous, Asterolecaniidae, can occur on bark of the trunk, branches, the underside portion of leaves, and produce a white-like powder. Horticultural and mineral (petroleum distillates) oils (1 to 1.5%) and certain systemic insecticides are preferred chemicals for most situations when scales are numerous enough to cause damage. Another scale, the wax scale *Ceroplastes janeirensis*, also can infect jaboticaba trees causing some damage; however, severe damage is observed only from soft scale infestation.

Black citrus aphid, *Toxoptera aurantii*, also can infest jaboticaba fruits (Gallo, 1988). The aphids feed by sucking sap from the small fruits, causing fruit distortion and malformation of growth reducing the quality. Several natural enemies of the black citrus aphid keep this pest under control, sometimes to the extent that insecticides are usually unnecessary. This pest is also controlled by the entomogenous fungus *Acrostalagmus albus* (Mau and Kessing, 1992).

Arapuá bee, *Trigonas spinipes*, may destroy the fruit as these bees eat the pulp of jaboticaba fruits. The control of this bee is carried out by removing or destroying the globular nests on the orchard outskirts.

According to Balerdi *et al.* (2006), birds and animals frequently eat the berries and can cause serious damage. To protect the crop, double-folded newspaper pages are placed around individual clusters and tied at the top (Morton, 1987).

11.9 Postharvest handling practices

11.9.1 Harvest operations

Fruit harvest occurs between one and one and a half months after bloom and differs by season according to the growing area.

Harvesting is done manually and carefully as jaboticaba is delicate and very susceptible to bruising. Harvesting is tedious and expensive as the fruit have to be harvested individually on the trunk and branches (Donadio, 2000; Balerdi *et al.*, 2006). Since jaboticaba do not ripen after harvest the fruit should be harvested when it reaches its full size and purple color, around 64 DAB (Figures 11.4 and 11.5).

Harvested fruit, packed in boxes or baskets, should be stored in the shade, as fruit left in the field exposed to sun can dehydrate and temperature can build up.

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11.9.2 Packinghouse practices

Today, growers are limited to harvesting the fruit manually when it has typical dark purple coloration and is mature. The fruit is placed in plastic buckets with a capacity of 10 L and quickly transported in order to avoid problems with compression.

At the packinghouse fruit are sorted in order to exclude all damaged fruit, which are misshapen, stained or show signs of decay. After sorting, fruit can be washed with chlorinated water (100 mg L^{-1}), to remove dirt and reduce contamination, dried using forced ventilation and mechanically classified by size to small (<10 mm), medium (10–20 mm) and large (>20 mm), and immediately packed. Waxing can be applied after washing and has been tested as aqueous solution. Duarte *et al.* (1997) tested 'Brogdex' Tomato Wax, 1:200 (v:v), and Corrêa (2006) tested 'Sta Fresh' wax at 2–3% of solids with good results.

Wooden boxes with a capacity of 18–20 L are commonly used. These boxes do not protect the fruits and also allow injury due to compression. Corrugated cardboard boxes, with a capacity of 4.5 kg or smaller, are increasingly used and have proved to be the most suitable for this fruit.

Jaboticaba fruit must be marketed quickly, preferably on the day of harvest, because it is quite perishable. The use of cooling to 10–12 °C (Duarte *et al.* 1997; Corrêa, 2006) can greatly increase its shelf-life but requires the maintenance of a cold chain from grower to consumer.

Wrapping of jaboticabas with LDPE films of 0.012 to 0.020 mm thickness reduced water loss in ambient or in cold storage conditions (Brunini *et al.*, 2004; Machado *et al.*, 2007).

11.9.3 Recommended storage and shipping conditions

In order to maintain fruit quality, jaboticaba should be refrigerated immediately after harvest. The best temperature range is from 13 to 15 °C (Cantwell, 2001), but lower temperature (12 °C) is also beneficial (Duarte *et al.*, 1997).

No information is available, but due to the rapid senescence of jaboticaba, ethylene might build up during storage. In this regard 1-methylcyclopropene (1-MCP) and/or other ethylene elimination systems, such as the use of potassium permanganate ($KMnO_4$) sachets, should provide some protection.

Wrapping seems essential with either plastic films or wax in order to avoid water loss that is a limiting factor for jaboticaba shelf-life. According to Balerdi *et al.* (2006), wrapping and/or the use of small plastic containers such as plastic wrapped strawberry, blueberry/blackberry baskets or clam shells, dramatically increase shelf-life with refrigeration and this is the way to pack and store jaboticaba fruit.

Durigan *et al.* (unpublished data) studied CA storage and stated that better quality was obtained in an atmosphere containing 5% O_2 at 12.5 °C. The ethylene level should be kept below 1 mg L^{-1} (Cantwell, 2001).

In mixed loads jaboticaba can be stored or transported with atemoya, banana, breadfruit, canister, casaba melon, crenshaw melon, mamey, rambutan, sapodilla, sapote, soursop, cherimoya, honeydew melon, jackfruit and mango (Cantwell, 2001).

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When shipped without refrigeration the fruit must reach the market in one or two days (Balerdi *et al.*, 2006). Refrigerated trucks have to be used in order to transport fruit to distant markets and, with the present knowledge, air freight may be the only method to reach markets overseas.

11.10 Processing

11.10.1 Fresh-cut processing

Jaboticaba is quite convenient to eat and, as previously reported, is eaten by squeezing the fruit between the thumb and forefinger, causing the skin to split and the pulp to slip into the mouth (Morton, 1987). Because the skin is thrown away, one might think of removing the skin and selling the fruit as fresh-cut produce. However, the appearance of the white and somewhat transparent pulp might not be attractive for consumers, although clean and sanitized whole fruit can be used in individual and/or mixed packages as fresh-cut fruit produce.

11.10.2 Other processing practices

Fruit should be processed without delay in order to maintain its quality and avoid fermentation. Jaboticaba can be used in a variety of ways for home consumption. Besides being eaten raw, the fruit can be juiced for jellies, preserves, wines and, most notably, liqueurs.

It is noteworthy that the main bioactive compounds of jaboticaba are in the skin, and they include phenolic compounds (Morton, 1987) and anthocyanins (Einbond *et al.*, 2004; Reynertson *et al.*, 2006; 2008). Therefore, the manufacture of processed produce using the skin may retain these compounds and add extra value to them.

Liqueur

In Brazil, the custom of using jaboticaba fruits to make liqueurs probably dates back to colonial times. The infusion is produced at home for family use according to a very simple recipe: ripe fruits are steeped in a Brazilian spirit (*cachaça*) with table sugar added. According to Lima *et al.* (2008), this product is generally very sweet and low in alcohol, and the use of *cachaça* brings a mediocre flavor.

Excellent liqueurs can be produced by squeezing 500 g of big, mature, clean and dry jaboticabas in one liter of good quality alcohol at 85°GL and leaving it to macerate for 15 to 20 days. After that, the skin and seeds are removed, the liquid is left for one week following by sieving, clarification and filtering, and after these operations one liter of sugar syrup is added. This syrup can either be flavored with vegetable extracts or not. The syrup is prepared by dissolving 1.25 or 1.8 kg of sugar in one liter of water at ebullition temperature under constant agitation. The clarification using albumin and bentonite may help to facilitate flocculation and sedimentation. Filtering though paper or cellulose paste under vacuum produces transparent, limpid, shiny and naturally ruby colored liqueurs (Geöcze, 2007; Lima, 2008).

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Table 11.7 Phenolics, tannins, anthocyanins and antioxidants of different jaboticaba [*Myrciaria jaboticaba* (Vell) Berg] liqueurs

Liqueur	Phenolic ($g\ L^{-1}$)	Tannins ($g\ L^{-1}$)	Monomeric anthocyanin ($mg\ L^{-1}$)	Polymeric anthocyanin (%)	ABTS 5 min. (% inhib.)	TEAC 15 min. ($mmol\ L^{-1}$)
A	0.52	0.47	9.70	81.50	53.63	2.48
B	1.08	0.64	6.06	89.24	66.28	3.12
C	1.20	0.75	10.72	80.70	76.01	3.61

Notes: A, maceration without heat treatment and syrup prepared under heat; B, maceration with heat treatment and syrup prepared under heat; C, osmotic dehydration and maceration

Source: Geöcze (2007)

Geöcze (2007) reported different content of phenolic compounds (0.52 to 1.20 g L^{-1}), tannins (0.47 to 0.75 g L^{-1}), monomeric anthocyanins (9.70 to 10.72 mg L^{-1}) and antioxidant capacity (2,2′-azino-bis 3-ethylbenzothiazoline-6-sulphonic acid – ABTS) (53.63 to 76.01% inhibition) and trolox equivalent antioxidant capacity (TEAC) (2.48 to 3.61 mmol L^{-1}) in jaboticaba liqueurs (Table 11.7). The phenolic content was lower than that found in red wine (1.64 g L^{-1}), but similar to rosé wines (0.80 g L^{-1}). Wines produced with 'Cabernet Sauvignon' grapes have more tannins (0.90 to 1.90 g L^{-1}), but the antioxidant capacity expressed as TEAC was similar to that of rosé wines (1.52 to 3.20 mmol L^{-1}) (Pellegrini *et al.*, 2003). It is noteworthy that osmotic dehydrated jaboticaba fruits (liqueur) produced a higher level of both chemicals and functional properties.

Wine

The aboriginals made wine from the jaboticabas, which is still done to a limited extent in Brazil (Morton, 1987). Lima (2008) also reported the production of wines from jaboticaba fruits. The juice from the fruit is extracted, pre-clarified by sieving, decanted, enzymatically treated, the acidity and sugar content are corrected, and it is inoculated with yeast and left to ferment. During the process, racking is necessary to eliminate lees which are formed. After fermentation the liquid is clarified and bottled. Ethanol content of 10.5 to 12% is recommended for good conservation (Lima, 2008).

Silva *et al.* (2008) studied the chemical composition of jaboticaba wines collected from different producers and reported that they did not meet the Brazilian standards for grape wines, with negative correlation between pH and volatile acidity, total acidity, and volatile acidity and alcohol content (Table 11.8). Sulphitation lowered volatile acidity and also improved alcohol content.

Jelly

Jaboticabas are often used for making jelly (jam). A portion of the fruit is mashed into a pan and sufficient water is added to cover the mass. Then it is boiled until the liquid turns a strong purple color, and skin and seeds are removed by sieving.

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Table 11.8 Total acidity (TA), volatile acidity (VA), alcohol content (AC) and pH of jaboticaba wines

Producer	Type	Total acidity (meq L^{-1})	Volatile acidity (meq L^{-1})	Ethanol content (°GL)	pH
1	Sweet white wine	279	7.5	15.4	3.20
1	Sweet red wine	206	18	13.2	3.50
1	Dry red wine	229	17.5	11.3	3.50
2	Dry white wine	162	25	11.4	3.30
2	Sweet white wine	202	13	13.8	3.40
3	Sweet red wine	134	10	13.5	3.60
4	Sweet red wine	208	10.2	14.0	3.40
4	Sweet white wine	145	20	13.0	3.60

Source: Silva *et al.* (2008)

In another pot the same volume of liquid and sugar are mixed, and this mixture is boiled. The jelly is placed in sterilized warm jars which are sealed while still warm. Some authors recommend the addition of pectin, and Morton (1987) recommended the removal of the skin from at least half the fruits in order to avoid a strong tannin flavor.

Vinegar

Acetic fermented products are also reported as a way to process jaboticaba fruits (Lima, 2008). The product is a result of acetic fermentation of jaboticaba wines with about 5 to 10% ethanol by volume. The ethanol is oxidized to acetic acid by acetic acid bacteria. Although jaboticaba vinegar is not common it can be produced during particularly good fruit harvests.

11.11 Conclusions

Jaboticaba is a fruit whose economic and nutraceutical potential has been highlighted by several studies, but it has received little attention outside of its native area. There is a need to establish new techniques for vegetative propagation in order to obtain plants that are increasingly productive, with a reduced juvenile period and with the capacity to bear uniform and desirable fruits. The jaboticaba tree suffers from few pest problems and is adaptable to a wide variety of soil types in tropical and subtropical regions.

Investigations to improve postharvest practices and to extend the shelf-life are also necessary, especially regarding cold storage and the use of modified and controlled atmospheres. The importance of ethylene after harvest, its determination and control, and the use of inhibitors such as 1-methylcyclopropene need to be further investigated.

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11.12 References

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Plate XX (Chapter 11) Development of flowers into fruits of the *Myrciaria jabuticaba* (Vell) Berg (jabuticaba 'Sabará'). (a) external tree aspect; (b) production aspect; (c) Blossom; (d) 4 DAB; (e) 7 DAB; (f) 11 DAB; (g) 16 DAB; (h) 28 DAB; (i) 45 DAB; (j) 50 DAB; (k) 60 DAB; (l) internal tree aspect. Source: Durigan, 2009.

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12

Jackfruit (*Artocarpus heterophyllus* Lam.)

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Abstract: This chapter deals with the important features of jackfruit composition, growth, maturation and harvest. Postharvest handling methodology concentrates on the normal packhouse unit operations with emphasis on packaging of bulbs as a unit package for retail marketing. The chapter further describes various value added products developed from jackfruit such as minimally processed, dehydrated, frozen and canned bulbs as well as ready-to-serve beverages, fruit bars and curry. The various by-products from seeds, unfertilized floral parts, and the outer perianth are also discussed. These products include starch from the seeds, leather-like products from unfertilized floral parts and pectin from the outer perianth portion. Finally, future requirements for improving the commercial utility of jackfruit are also highlighted.

Key words: *Artocarpus heterophyllus*, postharvest, jackfruit, bulbs, processing, handling.

12.1 Introduction

12.1.1 Origin, botany, morphology and structure

Jackfruit (*Artocarpus heterophyllus*), a giant and unique tropical composite fruit, is grown extensively in equatorial countries in the Indian sub-continent and South-East Asia, such as Myanmar, and also in South American countries such as Brazil. In India, the jackfruit tree grows and produces fruit in different parts of the country, including the southern states, Assam, Bihar and the central Himalayas. The tree is a huge perennial tropical with massive amounts of foliage. Its leaves are thick, rubbery, glossy and dark green in colour. The fruits, which grow on the trunk or the main branch, are gigantic, ranging from 10 to 25 kg in weight depending on the cultivar and agro-climatic zone. The fruit is popular and has various common names, including *Gulabi*, *Champa Hazari*, *Singapore* or *Ceylon Jack*, *Kapa Benka*, *Muttam Varikha* (Samaddar, 1985).

Jackfruit is a composite or multiple fruit (syncarp). It is reported to consist of three regions: the fruit axis, the persistent perianth and the true fruit (Ong *et al.*, 2006). The

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perianth, which constitutes the major bulk of the fruit, comprises a central core, a seed bearing region and the aril (together known as bulbs) and the outer layer in the form of a horny non-edible region. According to Elevitch and Manner (2006) the horny non-edible region is a green to yellow-brown exterior rind that is composed of hexagonal bluntly conical carpel apices covering a thick rubbery whitish to yellowish wall. Each seed is covered with a fleshy aril which is golden-yellow in colour and has a strong, sweetish taste. The central fibrous core holds the heavy fruit together. Elevitch and Manner (2006) state further that the fruits are oblong, cylindrical in shape and typically 30–40 cm in length, but sometimes may be as long as 90 cm. The maximum weight of the fruit is reported to be 50 kg (Morton, 1987). Elevitch and Manner (2006) also reported that fruits take 90–180 days to reach maturity. In the northern hemisphere the main bearing season is late spring to early fall (between March and September). However, a few fruits mature in winter also.

12.1.2 Worldwide importance

Jackfruit is grown in many countries including India, Myanmar, China, Sri Lanka, Malaysia, Indonesia, the Philippines, Brazil, Surinam, Caribbean islands, the US (e.g. Florida), Australia and some African countries. Many Pacific islands such as Fiji and Papua New Guinea are also known for their ability to produce jackfruit. The fruit grows as a backyard tree in the Hawaiian islands. The species is also reported on islands such as Palau, Yap, Pohnpei, Nauru, Tabiteuea in Kiribati and Samoa (Fosberg *et al.*, 1979).

Jackfruit belongs to the genus *Artocarpus*, which includes species such as breadfruit (*Artocarpus altilis*), dugdug (*Artocarpus mariannensis*) and breadnut (*Artocarpus camansi*). These species are important traditional fruit trees of the Pacific islands and India. Other major species in the genus *Artocarpus* include champedak (*Artocarpus integer*), lakoocha (*Artocarpus lakoocha*), marang (*Artocarpus odoratissima*) and kwai muk (*Artocarpus lingnanesis*) (Elevitch and Manner, 2006). All these species of the genus *Artocarpus* are similar in terms of the general morphology of the fruit, but upon ripening they differ both in taste and in composition. Some species, such as breadfruit, are used extensively as a source of starch, and in many African countries they are commonly employed as a flour extender in breadmaking. Two principal fruit types can be distinguished: (i) fruit with fibrous and mushy edible pulp, with a very sweet flavour and a strong odour, and (ii) fruit with thick, crisp and less fragrant pulp. In Hawaii, the major grafted cultivars are 'Black Gold', 'Dang Rasimi', 'Gold Nugget', 'Honey Gold' and NS1 varieties. In India the popular varieties of jackfruit are usually divided into two major groups: (1) soft pulp varieties, e.g., *ghula*, *vela*, *koozha*, *ghila*, *tsjakapa* or *kappa* and (2) hard pulp varieties, e.g., *varikka*, *varcha*, *kujja*, *karcha*. (see Plate XXI in the colour section between pages 274 and 275.) In addition to the above, Dutta (1956) described a third variety, a smaller jackfruit known as a *rudrakshi*. The other varieties known in India include *gulabi*, *champa*, *hazari*, *kapa benka* and *muttam varikha* (Berry and Kalra, 1988). The inter tree variability of fruit quality in jackfruit selection found in the Western Ghats of India was

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described by Jagadeesh *et al.* (2007a). It was found to be maximal in terms of seeds per fruit and brix:acid ratio, demonstrating the need for an improved selection process if commercially useful varieties of jackfruit are to be bred. Maia *et al.* (2004) reported flavour variation in the soft-pulped variety of Amazonian origin, while Rahman *et al.* (1999) highlighted the compositional changes and morphological and anatomical characteristics of soft and firm varieties of jackfruit from Bangladesh.

12.1.3 Economic value and overview of major uses

Jackfruit is of significant economic value. India alone has an annual production of jackfruit amounting to 1.07 million tons with a production area covering 0.51 million hectares (Ukkuru and Pandey, 2006). However, the commercial potential of the fruit is yet to be fully exploited and it is still commonly sold in the form of individual fresh bulbs by local vendors (Plate XXII).

A number of factors could be responsible for the low commercial utilization of jackfruit and for the product's lack of popularity, including: high flavour intensity, which may be undesirable to some consumers; the fruit's extremely sweet taste combined with lack of sufficient acidity; the popular association of jackfruit with poverty; the absence of commercial vegetative propagation methods; the lengthy gestation period for fruit development; and lastly, the large dimensions of the fruit. Jackfruit is a heavy fruit and contains a large proportion of inedible tissue in the form of unfertilized floral parts, the spiny outer skin and the large number of seeds. In fact, edible portions amount only to 30–35% of the total weight. Transportation and packaging costs are consequently very high, and it is virtually impossible to pack the fruit in conventional corrugated boxes. These factors create barriers to the sale of the unprocessed fruit outside local markets. Therefore value-added products (e.g. products created by separation and packaging of pitted bulbs) are more relevant commercially. As mentioned above, the limited propagation methods and lack of availability of improved varieties also limit the realization of the economic potential of jackfruit. Most of the varieties are wild, necessitating the introduction of more grafted or bred varieties. Selection needs to be improved even in the wild varieties in order to decrease inter tree variability and to optimize the yield and sensory attributes required for the global marketing of the fruit or its value-added products.

A number of value-added products have been reported, including nectar, leather, minimally processed (MP) bulb slices, canned and dehydrated products, and bulbs preserved by freezing and by hurdle technology. These products are shelf stable and are excellent delicacies suitable for global marketing. The seeds and the unfertilized parts of the flower also have economic value (Che Man and Sin, 1997). According to Elevitch and Manner (2006), jackfruit can also be fermented and distilled to produce an alcoholic beverage. The leaves, as well as the waste from the fruit after removal of bulbs and seeds, are useful as fodder. The wood of the jackfruit tree is generally considered superior to many other types of wood for making furniture, masts, oars and musical instruments. The latex produced by the tree is used as a chewing gum, and is also known to have

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bactericidal properties, similar to that of papaya latex. When heated it can be employed as glue in chinaware and pottery. The bark of the tree has a high content of tannins, and when boiled with alum it yields a clothing dye. Dried branches of the jackfruit tree are used to produce fire by friction in religious ceremonies in the Malabar region (Morton, 1987).

Jackfruit trees can be planted to avoid soil erosion and can be used as windbreaks to protect other crops (Elevitch and Manner 2006). The trees can also provide shade for crops such as coffee, pepper, betel nut and cardamom, with trees usually planted at a spacing of 15 × 15 m due to the deep shadow cast by their foliage. Jackfruit is used in many countries as an intercrop with coconut, mango and citrus fruit, and is very popular in home gardens because of its thick and beautiful foliage, high productivity and ornamental appearance.

12.1.4 Medicinal value

The various parts of the jackfruit tree, including the fruit, are used for several medicinal purposes. In China, the pulp and seed are used as a cooling tonic and as a remedy for overcoming the influence of alcohol in the body. Roasted seeds are regarded as having aphrodisiac properties, and ash from jackfruit leaves is commonly used as a healing treatment for ulcers. When dried, the latex from the plant yields artostenone, which can be converted to the compound artosterone; the latter is known to exert androgenic action. When the latex is mixed with vinegar, it promotes the healing of glandular swelling and snake bites. The root and its extract are known as a remedy for skin disorders, asthma and diarrhoea. The wood has a sedative property and it is believed that it may be used to promote abortion (Morton, 1965). Renowned Ayurvedic and Unani practitioners have found that jackfruit is useful against various ailments including leprosy, ulcers, constipation, heart disease and rheumatism (Devaraj *et al.*, 1985; Mukherjee, 1993), which could be attributed to the significant dietary fibre of the fruit. Balbach and Boarim (1992) reported the beneficial effects of leaves and stem bark in the treatment of anaemia, asthma, dermatitis and coughs. The fruits, seeds and wood of the trunk are believed to contain chemical compounds with aphrodisiac properties (Ferrao, 1999).

12.1.5 Culinary uses

Jackfruit is eaten and used in cooking both in its immature and in its ripe form. Immature jackfruit is used in curry preparation as well as to make pickles. The perianth of the fruit is usually cut into small pieces with a sharp knife and the pulp is known for its meaty texture. The curry made from the immature fruit is usually spiced with mustard powder during preparation, and similarly, large chunks of the immature fruit can be pickled in brine with mustard seed seasoning to obtain delicious pickles with excellent texture. The young fruit is rich in starch and in many tropical countries it forms part of the staple diet.

The ripe fruit with bulbs of a golden yellow colour is consumed as is necessary after pitting to remove the seeds. The unfertilized floral parts are removed from

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the fleshy bulbs to obtain delicious fruit segments with a firm texture and sweetish flavour and a typically strong aroma. The aroma of the fruit is intense and can be detected from a long range, making it easy to identify the presence of jackfruit in the near vicinity. As mentioned earlier in section 12.1.3, a number of value-added products are prepared from jackfruit bulbs including leather, crisps, osmo-dehydrated products and various other minimally processed and hurdle technology based products. The pulp is also used as flavouring in ice cream and beverages.

The seeds can be consumed after boiling or roasting, and a delicious curry can also be prepared from the cut seeds. Dehydrated and salted snacks based on jackfruit seeds are also popular, and cooked and dried seeds can be milled to obtain a flour-like consistency and used as a starch extender in bread dough. The tender young leaves are cooked and consumed as a vegetable product, and young male flower spikes can be grated or mashed for use as vegetables, or pickled with salt and vinegar.

12.2 Fruit growth, respiratory behaviour and ripening

The jackfruit tree grows rapidly, and reaches a height of 10–14 metres. Trees can live to more than 100 years old, and a 20-year-old tree can reach 17–18 metres in height and 25 cm in diameter. After 20 years, however, productivity decreases, necessitating removal and replacement. The tree usually takes 4–14 years to bear fruit, with the fruit of most cultivars reaching maturity in mid to late summer. However, in Asia varieties may ripen from March to June, April to September or June to August, depending on the climate (Morton, 1987). Jackfruit seedlings grow slowly in deep shade, and weeding must to be carried out to reduce competition for water, light and nutrients.

Jackfruit respiratory behaviour follows a typical climacteric pattern with three distinct phases of respiration (the pre-climacteric, climacteric and post-climacteric stages). Pre-cut immature fruit slices showed a basal respiration rate of 160 mg $CO_2h^{-1}kg^{-1}$ fruit and in the climacteric phase the peak of respiration was 245 mg $CO_2h^{-1}kg^{-1}$ fruit (Selvaraj and Pal, 1989). The climacteric peak was attained after 3 days of ripening. After 8 days of ripening, the respiration rate had dropped to a residual level of 60–70 mg $CO_2h^{-1}kg^{-1}$ fruit. No published literature exists on the synthesis of ethylene during jackfruit ripening; however, Saxena *et al.* (2008) described the ethylene synthesis pattern during modified atmosphere (MA) storage of pre-cut jackfruit bulbs after removal of seeds. The ethylene synthesis during MA storage showed a slight increase during the initial phase of storage followed by a slight decrease towards the end of MA storage.

12.3 Jackfruit composition and nutritional value

Several authors have described the chemical composition of jackfruit in immature and ripe forms, including Samaddar (1985), The Wealth of India (1985) and Bhatia *et al.* (1955).

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12.3.1 Volatiles

Esters are the dominant volatiles in jackfruit. Its volatile constituents include isopentyl isovalerate (28.4% of total volatile compounds) and butyl isovalerate (25.6%), followed by palmitic acid (8.3%) and ethyl isovalerate (6.2%). An aroma concentrate of soft jackfruit was dominated by isopentyl isovalerate, butyl acetate, ethyl isovalerate, butyl isovalerate and isopentyl acetate and isopentan-1-ol (Maia *et al.*, 2004). Rasmussen (1983), Sword *et al.* (1978) and Wong *et al.* (1992) gave a detailed description of the volatile constituents of jackfruit and confirmed that isopentyl isovalerate was particularly dominant. A total of 20 compounds were reported by Sword *et al.* (1978), 21 compounds by Rasmussen (1983) and 39 volatiles by Maia *et al.* (2004).

Ong *et al.* (2006) described the flavour profile during the ripening of jackfruit. It was observed that the number of volatiles increased during the ripening process. The principal component analysis (PCA) carried out by Ong *et al.* (2006) showed two principal components (PC), of which PC1 explained 85% of total variation and separated the sample mainly according to ripening. It was also found that the ester concentration was low during the first stage of maturity. Immature odour prevailed during the initial stage of maturity, formed from the reaction of alcohols and organic acids catalysed by alcohol acyltransferases, which are mostly active during fruit maturation (Olias *et al.*, 1995). After 5–6 days of ripening, jackfruit showed a significant presence of butyl acetate and 3-methyl butyl acetate, which contributed to the fruity and floral notes of the fruit. The appearance of both of these esters at the latter stage of ripening may indicate a fully ripened jackfruit.

12.3.2 Phenolic content

Jackfruit is a rich source of phenolic compounds including flavonoids. During storage of MP jackfruit bulbs, total phenolics were reported to an extent of 45 mg $100\,g^{-1}$ and flavonoids to an extent of 23 mg $100\,g^{-1}$ at the initial storage stage (Saxena *et al.*, 2009a). Immature jackfruit have a high phenolic content, giving them an astringent character; however, both phenolic and flavonoid content was found to decrease during the storage of the MP jackfruit bulbs stored under MA conditions. Stabilization of the bulbs with chemical additives and the synergistic effect of MA conditions reduced the loss in phenolics and flavonoids during storage. The antioxidant potential of the fruit tissue was also found to be at the maximum during the initial stage of storage for MP jackfruit bulbs, and decreased during storage over time. However, MA conditions and chemical pre-treatment could restrict the drop in antioxidant activity.

12.3.3 Acidity and crude fibre

Jackfruit is known to have high titrable acidity in the top and middle portion of the fruit and the citric acid content observed throughout the ripening process was found to be in the range of 0.3–0.9%. However, Selvaraj and Pal (1989) described a lower titrable acidity in the range of 0.1–0.2% (Table 12.1). The dominant organic

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Table 12.1 Changes in biochemical constituents during ripening of jackfruit (fresh weight basis)

Constituents	At harvest	8th day after harvest
Fruit firmness (kg/cm^2 pressure)	12	6.5
Pulp color (OD at 448 nm)	0.103	0.203
Dry matter (%)	30.1	23.9
Starch (%)	2.03	0.69
Sucrose (%)	2.9	8.7
Glucose (%)	0.8	4.9
Fructose (%)	1.3	6.6
Titrable acidity (% citric acid)	0.21	0.13
Brix:acid ratio	23.3	153.2
Total fatty acid (%)	0.139	0.169

Source: Selvaraj and Pal (1989)

acids present in jackfruit were malic acid and citric acid, with succinic and oxalic acids also identified. The organic acid content was found to decrease during ripening of the fruit, but not to any significant degree. Kays (1991) explained the decrease in organic acids during fruit ripening by stating that organic acid acts as a respiratory substrate and as a carbon skeleton for the new compound during ripening. There were no significant variations in crude fibre between different portions of the fruit, nor at different stages of ripening. The quantity of crude fibre fluctuates in the range of 0.33 to 0.40% during ripening (Ong *et al.*, 2006). The soluble fraction of the dietary fibre was found to be significant and comparable with other fruits. Levels of insoluble dietary fibre were found to be much higher than levels of soluble dietary fibre (Nahar *et al.*, 1993; Rahman *et al.*, 1999).

12.3.4 Total soluble solids (TSS)

It was reported that the increase in TSS content during jackfruit ripening could be attributed to the decomposition of the cell wall, causing the release of water-soluble compounds (Rees *et al.*, 1981). Reaves (1959) reported that the increase in TSS may be due to an increase in water-soluble galactouronic acid as a result of the degradation of water-insoluble pectic substances caused by the enzymatic activity of polygalactouronase. The top portion of the fruit had the highest TSS content, followed by the middle and lower portions. The ripening behaviour in terms of °brix change could show parallels with other fruits such as banana (Munasque and Mendoza, 1990). Sharaf and El-Saadany (1987) indicated that the increase in soluble solids could be attributed to the conversion of starch to sugars.

12.3.5 Carbohydrate and fatty acid content

Jackfruit is a rich source of carbohydrates including mono-, di- and polysaccharides. Ripe fruits are known to contain a high percentage of glucose, fructose and

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sucrose (Chowdhury *et al.*, 1997), which impart sweetness to the fruit (Berry and Kalra, 1988). Several other sugars such as rhamnose, xylose, arabinose and galactose have also been reported in the pulp of jackfruit (Sen Gupta and Rao, 1963).

Rahman *et al.* (1999) described the variation found in carbohydrate composition during the maturation process. In general, a progressive increase in the starch content was reported as the fruit grew. The authors analysed the jackfruit samples of different cultivars (soft and firm varieties) and reported a gradual increase in the total weight of the fruit, the total free sugars and the starch content. Several studies have examined the turnover of free sugar and starch (in other words, how starch is converted into sugar during ripening). Bobbio *et al.* (1978) isolated starch from the perianth of immature and ripe fruit and found that immature fruit has a starch content of 31.6% and 29.8% for soft and firm varieties respectively, compared to 2.2% and 9% for the ripe fruit (Rahman *et al.*, 1995). The ripe fruit contains higher levels of glucose, fructose and sucrose than the immature stage. The accumulation of these sugars during maturity is comparable with that observed in other fruits (Moriguchi *et al.*, 1990). Wills *et al.* (1986) have also conducted an in-depth study into the carbohydrate content of jackfruit.

Several investigations gave detailed accounts of different economically important parts of jackfruit including the perianth and seeds. The fatty acid composition and ethanolic and methanolic extracts of different parts of the fruit such as the inner edible perianth, inner non-edible perianth, inner stick, outer bark and the edible parts have all been the subject of extensive studies (Chowdhury *et al.*, 1997). Fatty acids such as capric, myristic, lauric, palmitic, oleic, stearic, linoliec and archidic acids have been reported to be present, with the first three being dominant. The variations in carbohydrate and distribution of free sugars and fatty acid in different parts of the ripe fruit have also been highlighted by Chowdhury *et al.* (1997). The abundance of different types of sugars and fatty acids in the profile of jackfruit bulbs suggests an active mechanism of sugar to fatty acid metabolism.

12.3.6 Vitamins, minerals, amino acids and other constituents

Jackfruit is rich in certain vitamins and minerals such as thiamine (39 μg 100 g^{-1}), riboflavin (130 μg 100 g^{-1}), phosphorus (41 mg 100 g^{-1}), potassium (88 mg 100 g^{-1}), calcium (90 mg 100 g^{-1}) and iron (0.5 mg 100 g^{-1}). It also contains significant amounts of vitamin A, with a content of 540 IU reported for the ripe fruit as well as a small quantity of vitamin C (7 mg 100 g^{-1}) in the edible tissue. However, the ripe fruit is deficient in thiamine and riboflavin, which are otherwise present in immature jackfruit (Bhatia *et al.* 1955).

Jackfruit contains about 1.9% protein on fresh weight basis (Table 12.2) (The Wealth of India, 1985). With regard to amino acids, the highest levels found were of phenylalanine, followed by aspartic acid and glutamine. Amino acid content was reported to be lower in the ripe fruit compared with the immature fruit.

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Table 12.2 Chemical composition of ripe jackfruit bulb (fresh weight basis)

Constituents	Value
Moisture	76.2%
Protein	1.9%
Fat	0.1%
Carbohydrates	19.8%
Fibre	1.1%
Minerals	0.9%
Calcium	20.0 mg/100 g
Phosphorus	41.0 mg/100 g
Iron	0.5 mg/100 g
Carotene	175.0 μg/100 g
Thiamine	0.039 mg/100 g
Riboflavin	0.13 mg/100 g
Niacin	0.4 mg/100 g
Vitamin C	7.0 mg/100 g

Source: The Wealth of India (1985)

Jackfruit is also an important source of other substances, including pectin. The pectin recovered from jackfruit has been purified and characterized for yields, moisture content and methoxyl value (Berry and Kalra, 1988). Enzymes found to be present in the fruit include amylase, invertase, pectinase and protease. Furthermore, both intra- and extra-cellular secretions of a strong pectolytic enzyme have been reported, which could account for the rapid cell breakdown observed after ripening.

12.3.7 Changes during ripening and inter tree variability

Many of the paragraphs above have mentioned changes in the chemical constituents of jackfruit during ripening. These have been extensively documented. According to Selvaraj and Pal (1989) during ripening there is a decrease in acidity, with an increase in tannin, sterol and fatty acid content. At the same time, levels of starch and alcohol insoluble solids decrease. In their study, sucrose levels surpassed those of glucose and fructose during the ripening process.

The significance of the inter tree variability in different physicochemical characteristics was highlighted in cluster studies carried out for jackfruit selection in the Western Ghats region of India. This variation could be due to genetic diversity in jackfruit (Maiti *et al.*, 2002). Rahman *et al.* (1995) found that the starch content of jackfruit showed a close correlation with maturity, variety and different climatic and agronomic conditions. Berry and Kalra (1988) also found a large degree of variability between different cultivars in terms of carotene and ascorbic acid levels, which are also influenced by the maturity of the fruit and by agroclimatic conditions. The significant differences between trees in levels of sugar, starch, carotenoids and acidity, seed numbers and mass, and fruit mass and

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length can be very helpful in selecting the right type of germplasm for vegetative propagation or breeding of improved cultivars of jackfruit.

12.4 Preharvest factors affecting fruit quality and harvest timing

Jackfruit plantations are few in India, as the trees are generally grown as fencing trees, avenue trees and in back gardens. Therefore, few preharvest studies on jackfruit have been carried out in India. However, the general agronomy, pest control and propagation methods (with limited emphasis on vegetative propagation) have been documented. The yield of jackfruit is 100–200 fruits per tree per year, and in India a good annual yield is considered to be 150 large fruits per tree. However, the yield is highly dependent on variety, cultural practice and environmental factors (Soepadmo, 1992). Trees must be planted with adequate spacing to allow sufficient ventilation for the growth of trees and development of fruits. Another significant preharvest factor is the prevailing agroclimatic conditions, including the temperature regime and humidity of the atmosphere, which affect jackfruit maturation. A significant physiological disorder associated with jackfruit is the breakdown of internal tissue at the centre pockets of the compound fruit, which could be due to mineral deficiencies in the soil. Appropriate supplementation of minerals such as Ca and Zn in the fields could help prevent the occurrence of this tissue breakdown.

The fruit should be harvested without causing mechanical damage, e.g. cuts or bruises. It is desirable to maintain at least 2–3 cm of the fruit stalk to avoid latex staining on the surface of the fruit. The fruit can be harvested when immature for subsequent ripening or when already ripe. The harvest maturity of immature jackfruit for subsequent ripening is generally stated to be 90–120 days after appearance of spikes (Berry and Kalra, 1988). A maturity study conducted at the Federal Land Development Authority (FELDA) in Malaysia found that immature fruit for subsequent ripening need to be harvested 100 days after bagging, equivalent to 16 weeks from anthesis (Punan *et al.*, 2000). In the case of ripe fruit, the following quality parameters are important: total soluble solids (22–24°Brix), total sugar content (11–15%) and titrable acidity (0.3%). Harvesting of ripe fruit must be carried out before the typical aroma of the fruit can be detected. It is commonly observed that when the mature fruit is ready for harvest, certain physical changes occur on the outer skin of the fruit: the gap between the spikes widens, and the colour of the fruit develops from dark green to light brown/green.

12.5 Postharvest handling practices

Literature on postharvest handling and storage of whole jackfruit is scarce, possibly due to the difficulties of storing and transporting the fruit mentioned in section 12.1.3. Significant issues are outlined below.

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After harvest, the fruit can be kept on coir net platforms with the cut end oriented towards the ground to prevent the latex from coming into contact with the fruit surface. The fruit may be graded according to size, as large fruits tend to yield larger bulbs than smaller fruits. After sorting and grading, rinsing with chlorinated water is a common phyto-sanitation measure adopted to remove dirt, foreign matter, latex, stains and field contamination. After washing with chlorinated water, fruit must be rinsed thoroughly to remove excessive moisture from the surface. Immature fruit should be kept for ripening at room temperature for 3–4 days, while ripening of mature fruit can be carried out in the packhouse. Uneven ripening is a major problem during ripening of jackfruit, particularly in the case of large fruit. The ripening may be uneven between fruits, or even within the same fruit, as the part of the fruit at the cut end may ripen earlier than that at the distal end. Induced ripening may be carried out by keeping the fruits in ripening chambers, and the ripening process may be accelerated by the introduction of ethylene (50 ppm) at a temperature of 25 °C. Exposure of the fruit to ethylene may be restricted to 24 hrs followed by opening of the doors of the chambers to allow normal ripening under ambient conditions. The fruit ripens within 3–4 days after treatment with ethylene gas. Another common practice on the Indian subcontinent is the insertion of V-shaped wooden wedges into the flesh of the fruit. The wounding process results in synthesis of ethylene at the cut end. The other methods adopted during jackfruit ripening include covering the fruit with natural fibre woven cloths or with paddy straw in order to facilitate the accumulation of natural ethylene within the fruit's immediate environment, accelerating ripening. Once the fruit have ripened, they are cut open using sharp knives to remove the core and to separate the bulbs. The separated bulbs after pitting can be size graded and packaged in over wrapped trays or flexible pouches for marketing purposes.

Packhouse operations, such as separation of bulbs and pitting, need to be carried out at 18–20 °C (however, during ripening of the fruit under ethylene-flushed conditions the temperature needs to be maintained at around 25 °C). Jackfruit, especially in immature condition, can be difficult to handle due to the presence of milky latex and mucilaginous exudates, which can stick to workers' hands and to knives. As a result, edible oil is often smeared onto the palms and the knife, or else non-stick gloves are employed. Multiple handling of the single fruit is avoided due to the risk of physical injuries to workers. Table 12.3 presents the details of different postharvest handling operations used for jackfruit.

Bulk storage of whole fruit is usually carried out at 12 ± 1°C and the packaged bulbs are stored at 5–6 °C. Water loss from the whole fruit is minimal as a result of the thick outer skin of the fruit Whole jackfruit kept at temperatures below 12 °C often show symptoms of chilling injury, characterized by softening, collapse of tissue, browning and surface pitting. The whole fruit is more susceptible to chilling injury than the pitted bulbs, which can be maintained at 5–6 °C. The lowest temperature that the whole jackfruit can tolerate is 2 °C.

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Table 12.3 Postharvest handling practices for jackfruit

Serial no.	Unit operation	Postharvest problem	Remedial measure	Limit	Tolerance	Preventive action
(1)	Inspection of fruit	(a) Immature or overripe fruit	(a) Sorting out fruits with blemishes, immature and overripe	(a) Unripe fruit non concessive for ripening and too much softening of the fruit	(a) Too soft affecting the texture of the fruit	(a) Following of appropriate harvest index
		(b) Infestation with fruit boring pests	(b) Rejecting infected fruits and adoption of infield bagging	(b) Softening of infected area	(b) 10% infected area	(b) Adopting of preharvest pesticide spray
(2)	Phyto sanitation	Incidence of contamination due to inferior quality of wash water	Chlorination to adequate level (at 100 ppm) and appropriate surface drying	Rotting of fruit	10% defective fruit	Ensuring hygienic water for phyto sanitation
(3)	Storage of fruit	Sub optimal storage temperature causing spoilage	Pre cooling is recommended and storage at moderate temperature	10–12°C	Higher and lower temperature not exceeded by 2°C	Adoption of sound cold room maintenance and management
(4)	Ripening quality	Non uniform ripening and over ripening	Use of ethylene gas to ensure uniform ripening	No uniform ripening	Within the same fruit and at least 50% ripe fruit shall be available for further handing from each fruit lot.	Appropriate adoption of alternative indices and grading protocols

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Table 12.3 Continued

Serial no.	Unit operation	Postharvest problem	Remedial measure	Limit	Tolerance	Preventive action
(5)	Separation of bulbs and pitting	Microbial contamination from un-hygienic handling, excessive physiological stress due to use of blunt edged knives and excessive temperature abuses during handling	Personal hygiene of paramount importance, use of appropriate knives with sharp edge made up of food grade SS and maintenance of handling temperature of 18–28°C	Personal hygiene codes to be followed meticulously, temperature of handling must not exceed 2°C, the metallic devices used for cutting of fruit and removal of bulbs must be of certified food grade equality	Zero tolerance in terms of personal hygiene, quality of metallic devices	Uncompromising phyto sanitation of handling rooms to be followed using standard plant hygiene measures
(6)	Fruit bulb packaging	Biological hazards can occur due to wrong use of commodity specific selectively permeable packaging films and also incorrect setting of O_2 and CO_2 concentrations within the packages	Use of optimal packaging films and maintenance of appropriate fill weight and head space within the packages	O_2 and CO_2 concentrations l evels needs to be monitored to ensure optimal maintenance around 3% O_2 and 5–6% CO_2	O_2 level not below 2% and CO_2 level not beyond 6%	Adoption of stringent modified atmosphere packaging, and testing of packaging failure on regular basis
(7)	Marketing	Temperature abuses during retail marketing can cause potential biological hazards	Strict adherence to storage temperature	4–6°C of storage temperature	Higher and lower temperature shall not fluctuate by more than 2°C	Establishment of authentic cold chain at bulk storage and related marketing levels

Source: Punan *et al.* (2000)

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12.6 Pathological disorders and insect pests

The principal pathological diseases affecting jackfruit are pink disease (*Pelliculana salmonicolor*), rotting of fruit and stem caused by *Rhizopus artocarpi*, and leaf spot due to *Phomopsis artocarpina* and other fungi. Grey blight, grey mould, charcoal rot, root rot, collar rot and rust may also occur (Elevitch and Manner, 2006).

The major pests affecting jackfruit include boring insects such as *Indarbela tetraonis, Betocera rufomaculata* and *Margaronia caecalis* (Morton, 1987). In India, the principal pests are the shoot-boring caterpillar, mealy bugs, spittlebugs and jack scale (Elevitch and Manner, 2006). In China, the fruit is often susceptible to larvae of longicorn beetles, caterpillars of leaf webbers, aphids and thrips. Pest management is of paramount importance in facilitating the growth of healthy fruit with maximum yield. The major pest control operations include pruning of the infested plant parts and use of pesticides such as methamidotrophos (Tamaron), monocrotophos (Azodrin) and dimethode (Rogor). Another practice adopted in pest control is the spraying of bagged fruit with fungicides such as carbendazim. The bagging of fruit can be carried out after two weeks of fruit set (Punan *et al.*, 2000).

12.7 Processing

Both ripe and immature jackfruits have been the subject of many studies on value addition. Immature jackfruit is very well-liked on the Indian subcontinent, and many popular products are made through dehydration, canning and hurdle processing of curried immature jackfruit. A number of products have also been developed from the ripe bulbs and from the pulp. The probable product profile of jackfruit in immature and ripe form is shown in Fig. 12.1.

12.7.1 Fresh-cut processing

Some studies have investigated ways to improve the quality and increase the shelf life of fresh-cut jackfruit. Punan *et al.* (2000) described a quality assurance system for minimally processed (MP) jackfruit bulbs. Saxena *et al.* (2008; 2009b) described a comprehensive minimal processing protocol inclusive of chemical conditioning and modified atmosphere packaging (MAP) storage for pitted jackfruit bulbs (Fig. 12.2). Preconditioning an MP jackfruit bulb was found to provide resistance towards microbial spoilage, browning, textural and oxidative losses of nutrients. Chemical conditioning in synergy with MAP gave the maximum shelf life of 27–35 days at 6 °C. The active mode of MAP involving flushing of polyethylene (PE) bags with a specific gas mixture (3 kPa O_2 + 5 kPa CO_2) was found to be superior to passive modes such as silicon membrane based gas diffusion PET jars and MAP in PE bags. Saxena *et al.* (2009a) also reported better retention of phytochemicals such as carotenoids, ascorbic acid, phenolics and flavonoids

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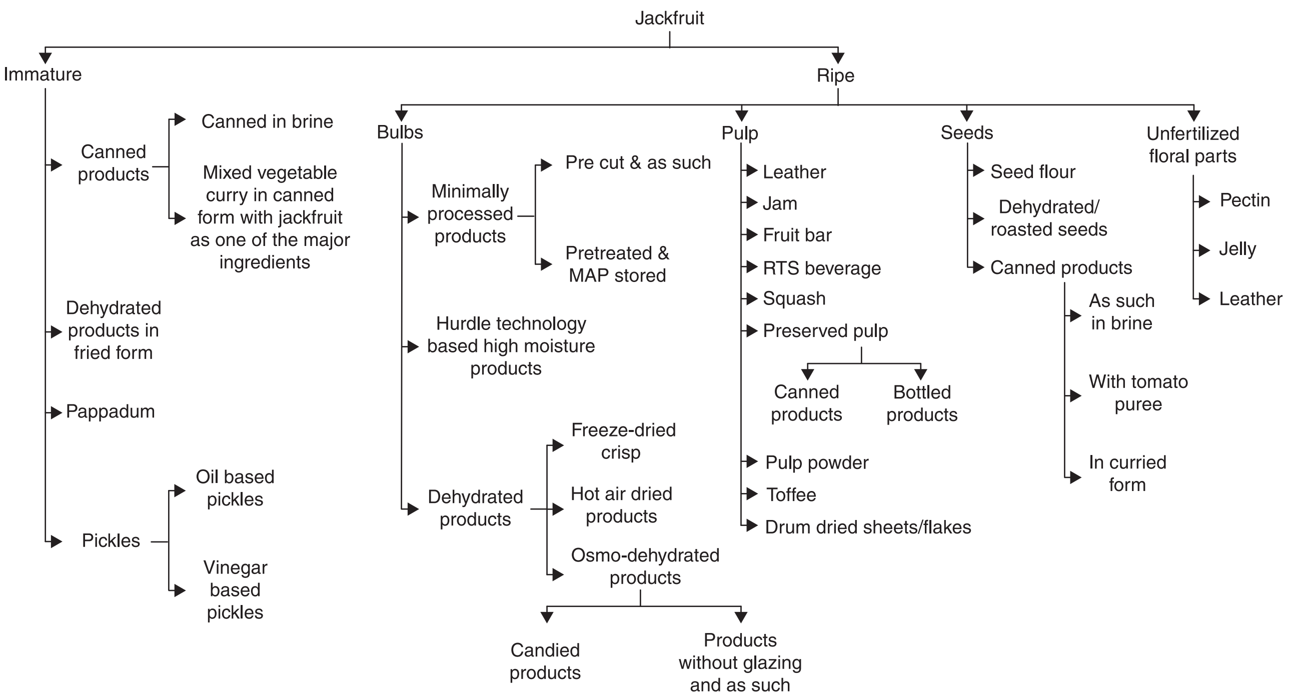

Fig. 12.1 Utilization of jackfruit as various products.

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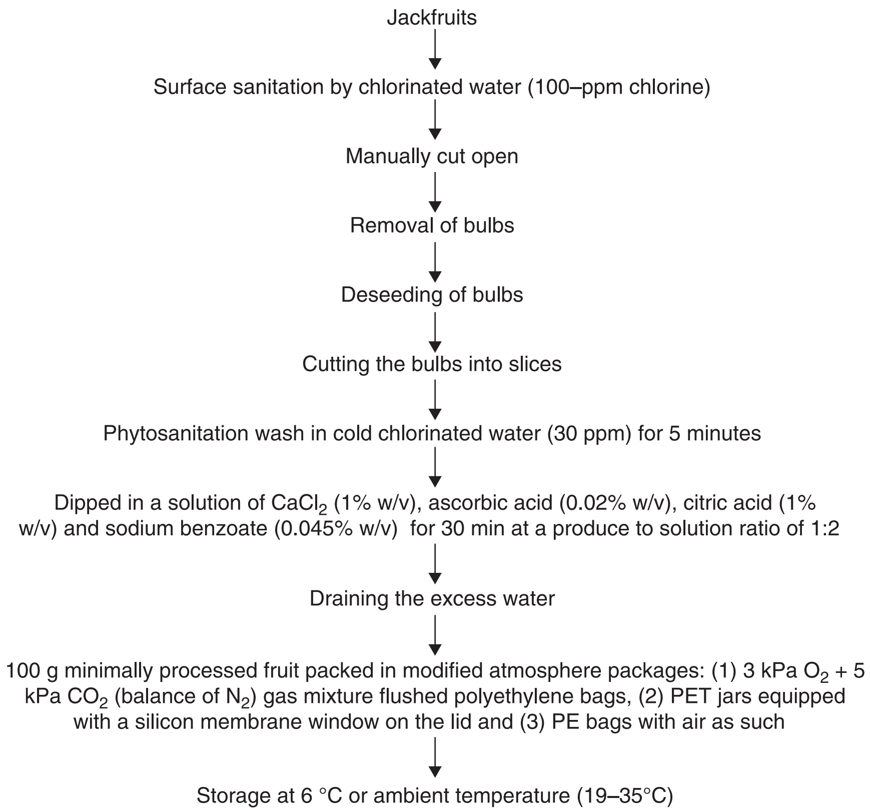

Fig. 12.2 A process protocol for minimal processing of jackfruit bulbs.

under the same MAP conditions. It has also been reported that pre-treating of jackfruit bulbs with chemical additives such as restricted quantities of calcium salt, ascorbic acid, citric acid and benzoate could further stabilize the product, enabling it to tolerate the MAP conditions effectively without microbial spoilage or incidence of pathogens (Saxena *et al.*, 2008). Saxena *et al.* (unpublished data) highlighted controlled atmosphere (CA) conditions suitable for the preservation of pitted jackfruit bulbs. Jackfruit bulbs can be stored under CA (3 kPa O_2 + 6 kPa CO_2) for 50 days. These reports suggest that jackfruit bulbs can be successfully subjected to MA/CA storage to obtain a shelf life of up to 30–50 days under low temperature (6 °C) conditions.

12.7.2 Other processing practices

Hurdle technology-based shelf-stable product

Saxena *et al.* (2009c) described a multitarget preservation technique for jackfruit bulbs by incorporating hurdles such as regulation of water activity (*a*w), acidification

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and in-pack pasteurization (Fig. 12.3). A shelf life of 6 months at ambient temperature was obtained for the product when variables such as osmotic solution concentration, temperature and immersion time were optimized. John *et al.* (1993) described the hurdle-based preservation of immature jackfruit curry in flexible pouches. Acidification, vacuum packaging and restricted thermal processing were used as the hurdles for the stabilization of the product and a shelf life of 4 months was obtained at ambient storage.

Dehydrated products

Dehydrated products from ripe jackfruit are popular due to their high sugar content, attractive colour and firm fleshy texture. Jagadeesh *et al.* (2006) described

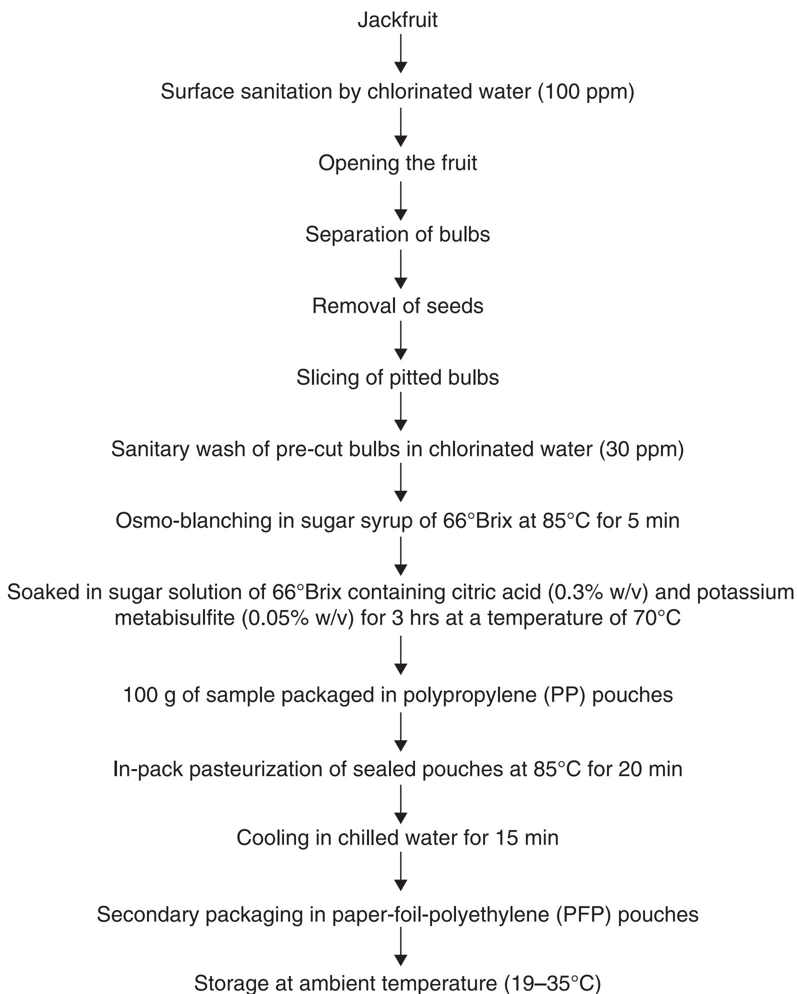

Fig. 12.3 A process protocol for hurdle technology based processing of jackfruit bulbs.

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the influence of dehydration on jackfruit bulbs. Several jackfruit cultivars from India were studied and their drying characteristics were analysed, with flack thickness, bulb length, soluble solids, total and reducing sugars as the process variables. The optimal range of reducing sugars was found to be 0.87% to 2.17%. The yield data was also compiled and the influence of dry matter content of different cultivars on yield was highlighted. Giraldo-Zuniga *et al.* (2006) modelled the kinetics of dehydration for jackfruit slices using a convective vertical tray drier, and the influence of variable dehydration temperature and the residual moisture content were analysed. The Fick diffusion model showed the maximum coefficient in terms of non-linear regression analysis. Saxena *et al.* (2010) determined the kinetic parameters for degradation of carotenoids and tri-stimulus colour coordinates of jackfruit slices during hot air drying at 50, 60 and 70 °C and evaluated the relationship between visual colour parameters (Hunter $L \times b$ values) and total carotenoids. Saxena, Bawa and Raju (unpublished data) described the combined dehydration method whereby both freeze dehydration and hot air dehydration are employed in order to obtain high quality jackfruit crisps, which can be consumed as they are, and may also be readily reconstituted as an instant product (Fig. 12.4). Drum-dried jackfruit sheets, which underwent subsequent powdering, were also developed (Pua *et al.*, 2007). The incorporation of soy lecithin and gum arabic was found to influence bulk density, colour, residual moisture content and overall sensory acceptability of the product. Optimal concentration was found to be 2.65% for soy lecithin and 10.28% for gum arabic and the responses were fitted in a second-order polynomial model. The additives were employed for emulsification and stabilization purposes, in order to obtain a double drum-dried product with optimal quality. Certain value-added jackfruit products have been developed from parts other than the bulb. Che-Man and Sin (1997) prepared a dehydrated fruit leather from the unfertilized floral parts of jackfruit. The products had a residual moisture content of 12–26%, fat of 0.26%, protein of 2.85%, crude fibre of 6.27%, ash of 0.87% and calorific value of 440 Kcal 100 g^{-1}. The product was stabilized at a aw of 0.6. Product stability was found to be satisfactory with optimal sensory attributes endorsed with sufficient chewiness (Che-Man and Taufik, 1995).

Beverages, jam and fruit bars

There is potential for the development of commercially useful beverages based on jackfruit, such as squashes and ready-to-serve (RTS) beverages. The pulp has excellent visco-elastic properties and adequate build up of soluble solids. The deep yellow colour of the pulp makes it ideal for carbonated and non-carbonated beverages. John and Narasimham (1993) described the processing of carbonated beverages from the unfertilized floral parts. The turbid homogenate was clarified with pectic enzymes to obtain 60% yield of clarified juice with a 25°Brix and 0.3% acidity. Carbonation was carried out at three levels, 0.775, 2.092 and 3.685 kg cm^{-2}, the first of which was found to be ideal. Krishnaveni *et al.* (2001) reported the development of an RTS beverage from two varieties of jackfruit. The product had 10% pulp, 18°Brix, and 0.25% acidity. During storage, levels of

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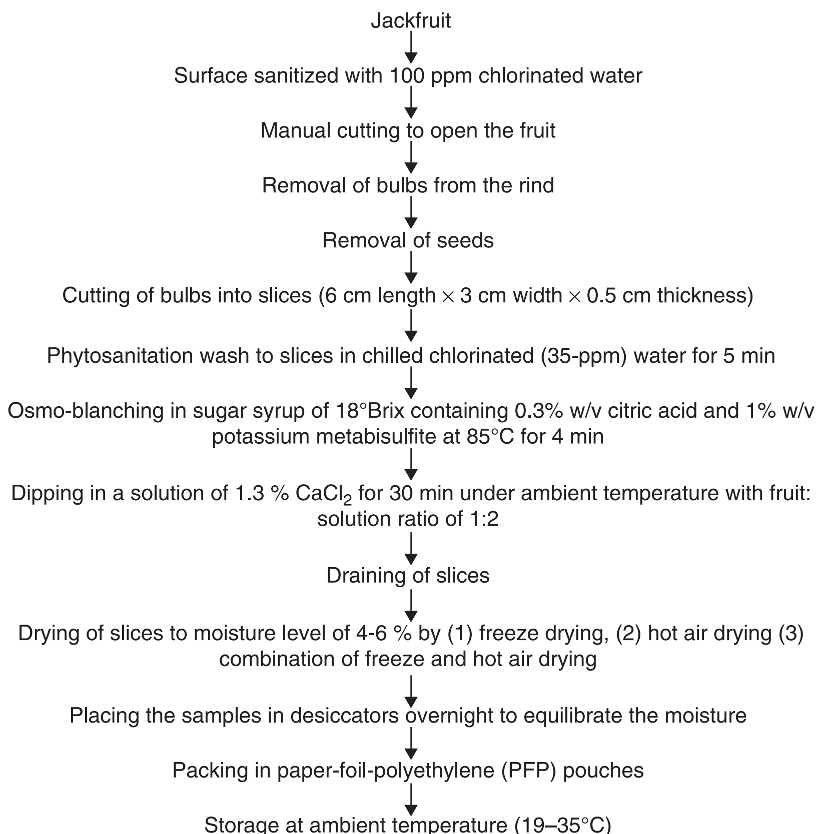

Fig. 12.4 A dehydration process protocol for jackfruit bulb crisps.

acidity and reducing sugar increased, while pH levels, along with the total sugar, ascorbic acid and β-carotene content, increased. The beverage was found to be highly acceptable even after six months of storage at room temperature. Jackfruit juice has also been packaged in cans (Seow and Shanmugam, 1992). The authors described the kinetics of internal can corrosion and vitamin C retention in plain tinplate cans, which followed zero-order kinetics during storage at 30–50 °C. The activation energy (E_a) followed the order of iron dissolution > tin dissolution > vitamin C depletion. The presence of nitrate accelerated all three processes without significantly affecting the E_a value. Tin dissolution, rather than depletion of vitamin C, appears to be the predominant factor limiting the shelf life of the product. It is estimated that appropriately processed jackfruit juice packaged in plain tinplate cans could keep well for 17 months at room temperature in the absence of nitrates.

A further potential use of jackfruit is in the preparation of jam and jelly due to the presence of adequate pectin content and the visco-elastic properties of the pulp. Jams and jellies can be developed as conventional products and as low calorie products by incorporation of non-nutritive sweeteners in the formulation.

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Manimegalai *et al.* (2001) also described the development of jackfruit bars. The storage stability of the product when packaged in different packaging materials, i.e. polypropylene/metalized polyester-laminated pouches, was analysed, and the shelf stability was found to be six months at room temperature. The product showed better shelf-stability when packaged in specific laminated pouches than when wrapped in butter paper or packaged in polypropylene pouches. Jackfruit pulp can also be used in mixed fruit bars in combination with the pulp of other fruits such as mango and pineapple. Its visco-elastic properties can play a substantial role in producing an adequate texture for a mixed fruit bar.

Frozen products

Jackfruit bulbs are ideal for freezing due to their firm texture and ability to withstand the process. John and Narasimham (1998) described the quality characteristics of blast frozen and cryo-frozen ripe jackfruit bulbs. The bulbs were packaged in cans and subjected to blast/cryo-freezing for storage at −18 °C. After six months of storage, cryo-frozen samples showed a toughness value of 1.42 kg cm^{-2} compared to the initial value of 1.62. In blast frozen samples, the toughness value was 1.29 kg cm^{-2} indicating greater toughness retention in the case of cryo-frozen samples. Cryo-frozen products also showed better colour retention as well as higher sensory value than blast frozen bulbs after six months of storage.

Products from immature jackfruit

Compared with studies on value addition relating to the ripe fruit, immature jackfruit has drawn less attention. Immature jackfruit is popularly used in curry preparation on the Indian subcontinent, and John *et al.* (1993) reported the use of hurdle processing in stabilizing curry prepared from immature jackfruit. The hurdles applied included acidification, vacuum packaging and in-pack pasteurization. The hurdles were found to be adequate to render the product microbiologically safe, giving an overall shelf life of 120, 270 and 360 days at storage temperature of 28, 4 and −18 °C, respectively.

Certain conventional practices are employed on the Indian subcontinent to produce pickles with extended shelf-life by immersing immature jackfruit in brine or vinegar. Immature jackfruit slices can also be subjected to dehydration to prepare dehydrated curry mixes. When powdered, immature jackfruit can be used as a flour extender, as is commonly the case with its close relative, the breadfruit. Kanzaki *et al.* (1997) described and established the phylogenetic relationship between jackfruit and breadfruit.

By-products from jackfruit

As already mentioned, there are several edible parts other than ripe bulbs within jackfruit. In ripe fruit, the seed and the unfertilized floral parts may also be eaten. Jackfruit seeds are rich in starch and when roasted are edible with a crisp texture. Ripe jackfruit seeds are also used in desserts or in culinary preparations. Jackfruit seed starch has a lower gelatinization temperature range than modified starch and requires less energy for gelatinization (Mukprasirt *et al.*, 2004). The peak viscosity

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of jackfruit seed starch was lower than that of commercially modified starch and the same trend could be seen in the case of set back velocity, swelling power and solubility of jackfruit seed starch. Because of its high thermal and mechanical shear stability, jackfruit seed starch could be an ideal replacement for modified starches. Singh *et al.* (1991) described the functional properties and protein quality of jackfruit seed flour. The protein content in jackfruit seeds was found to be 16.3% with 89% protein digestibility. The high solubility of jackfruit seed in the acidic reagent indicated that the protein might be used in the formulations of acid foods such as protein-rich carbonated beverages. Kabir (1998) described the isolation of a lectin known as 'jacalin' for versatile application in immunobiological research. It is a tetrameric two-chain lectin combining a heavy α chain of 133 amino acids residues with a light β chain of 20–21 amino acids residues. The lectin is specific for α-O-glycoside of the disaccharide antigen (Gal β 1–3 GalNAc). The outer perianth and peel of jackfruit and the unfertilized floral parts are a rich source of pectin, which could be commercially manufactured for high quality pectin.

12.8 Conclusions

As a giant tropical compound fruit with excellent flavour and textural quality, jackfruit has the potential to become popular in the global market. Outside of certain parts of the world such as South-East Asia and Florida, jackfruit has not received a large amount of attention due to the lack of authentic vegetative propagation methods, meaning that jackfruit is only popularly found as a kitchen garden tree or in avenue plantations rather than in commercial orchards. There is an acute need to develop appropriate propagation technology based on micro-propagation methods, and to bring information about soil requirements, agronomic practices, pest management and postharvest handling techniques to a wider audience. Modified atmosphere storage of jackfruit bulbs needs to be further investigated, in particular regarding the use of antifog film wraps and the application of active MA packaging methods by micro and macro climatic regulation of storage atmospheres. One of the foremost requirements in the value addition of jackfruit is the development of primary processing technologies such as thermal processing, freezing and chemical preservation of pulp in bulk containers. The marketing of bulbs stabilized by hurdle processing is very promising, as the product has a pleasant taste and an attractive colour. Jackfruit should not be considered suitable only for the poor, as its nutritional and sensory quality is competitive enough to earn it a place in the global market. Future work on nutrigenomics could potentially help in improving jackfruit quality for the satisfaction of different consumer sectors around the world.

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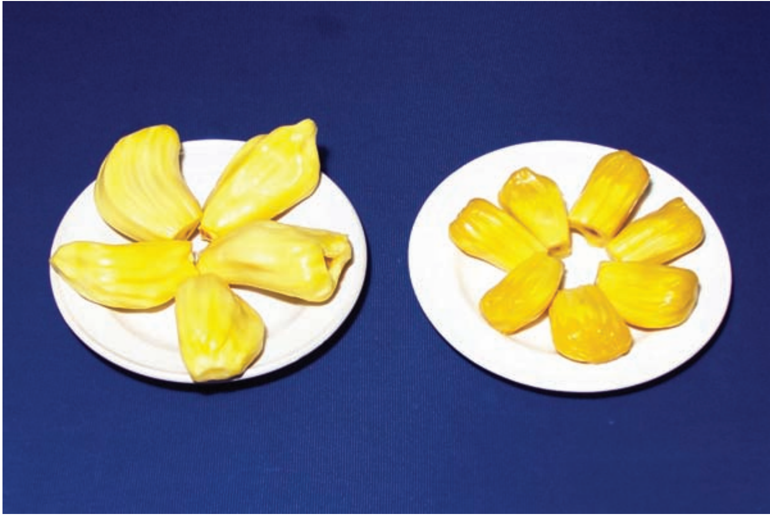

Plate XXI (Chapter 12) Hard and soft pulp varieties of jackfruit.

(a)

(b)

(c)

(d)

Plate XXII (Chapter 12) (a)–(d): Jackfruit being sold in the market of Mysore, India.

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13

Chinese jujube (*Ziziphus jujuba* Mill.) and Indian jujube (*Ziziphus mauritiana* Lam.)

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Abstract: Jujube fruits with high nutritional and medical value are consumed worldwide as fresh and dry fruit. This chapter discusses the origin and importance of the Chinese jujube (*Ziziphus jujuba* Mill.) and the Indian jujube (*Ziziphus mauritiana* Lam.), and describes their postharvest physiology, postharvest handling and storage, postharvest disorders, pathology, associated entomology and processing.

Key words: jujube, storage, processing, postharvest physiology, disorder.

13.1 Introduction

13.1.1 Origin, botany and morphology

Jujube is the common name for any of a genus of evergreen and deciduous shrubs and trees of the buckthorn family, classified as the genus *Ziziphus* of the family *Rhamnaceae* and order *Rhamnales*. The *Rhamnaceae* family comprises 50 genera and more than 600 species (Bailey, 1947) of which the species *Z. jujuba* Mill (Chinese jujube) and *Z. mauritiana* Lam. (called Indian jujube or ber) are the most important in terms of distribution and economic significance. Plants of the genus have small, regular flowers that produce drupaceous fruits. They are grown in tropical and subtropical regions all over the world. They are widespread in the Mediterranean region, Africa, Australia and tropical America (Pawlowska *et al.*, 2009). Some kinds of jujube such as Chinese jujube are native to warm regions of Eurasia, such as China, Korea and parts of southeastern Africa (Lin and Cheng, 1995).

The species *Z. jujuba* Mill (Chinese jujube) is indigenous to China, where its history of cultivation goes back over 4000 years. It has been widely planted in reforested areas within the Yellow River valley, chosen as a species compatible with the present ecology and economy (Yan and Gao, 2002). There are many varieties of

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Chinese jujube in different regions, with quite different colors, shapes, sizes and nutritional contents. (See Plate XXIII in the color section between pages 274 and 275.) The major varieties for *Z. jujuba* are 'Jinsixiaozao', 'Junzao', 'Dongzao', 'Lingzao', 'Jianzao', 'Xuezao', 'Sanbianhongzao', 'Fangchuizao', 'Budaizao', etc. Some varieties are suitable for fresh use, while some are better for processing as dried jujube. China produces about 90% of the world's jujubes for food and pharmaceutical applications (Yan and Gao, 2002). Chinese production itself has risen from 1.1 million tonnes in 1998 to 2.0 million tonnes in 2006 (Li *et al.*, 2005).

Much of the annual Chinese jujube production is consumed in fresh and dried forms; therefore, there have been numerous studies on the storage and processing of Chinese jujube in order to enhance its quality. The major cultivars of *Z. mauritiana* Lam. are 'Katha', 'Bagwari', 'Umran', 'Chhuhara', 'Illaichi', 'Karaka', 'Mundia' 'Murhra' and 'Narma'. In India, the ripe fruits are mostly consumed raw, but are sometimes stewed, whereas slightly under-ripe fruits are candied. Residents of Southeast Asia eat the unripe fruits with salt. Ripe fruits crushed in water are a very popular cold drink, or alternatively, the ripe fruits are preserved by sun-drying and a powder is prepared for out-of-season purposes. Acidic types of jujube are used for pickling or for chutneys (Pareek *et al.*, 2009). In China and Africa, the dried and fermented pulp is pressed into cakes resembling gingerbread (Pawlowska *et al.*, 2009; Shi and Qi, 2002). Jujube is also grown as an ornamental plant in southwestern regions of the United States.

13.1.2 Nutritional value and health benefits

Chinese jujube fruit is a favored and profitable fruit, and is much admired for its high nutritional value. It is commonly used as a food, food additive and flavorant. The *Ziziphus* species are commonly used in folk medicine for the treatment of various diseases such as digestive disorders, general weakness, liver complaints, obesity, urinary troubles, diabetes, skin infections, loss of appetite, fever, pharyngitis, bronchitis, anemia, diarrhea and insomnia (Han and Park, 1996; Kirtikar and Basu, 1975). For thousands of years, it has been commonly used as a crude drug in traditional Chinese medicine for analeptic, palliative and antibechic purposes.

According to analysis by the Food and Nutrition Board, National Research Council (1989), the average dried *Z. jujuba* sugar content is 50.3 ~ 86.9 g kg^{-1}, while the protein content is 3.3 ~ 4.0 g kg^{-1}, and fat content is 0.2 ~ 0.4 g kg^{-1} (dried weight basis). Chinese jujube also contains 18 kinds of amino acids, including eight essential amino acids, and is rich in vitamins and minerals. The ascorbic acid content is up to 500 ~ 800 mg in 100 g of fresh *Z. jujuba*, such as Chinese winter jujube (also called Dongzao). This level is higher than that of kiwi fruit (1~2 times), citrus (7~10 times) and apples (100 times) (Table 13.1). The species *Z. mauritiana* Lam. is mainly consumed fresh, has an ascorbic acid content of 65~280 mg 100 g^{-1} and is rich in essential minerals and carbohydrates (Table 13.1). The physico-chemical characteristics of major Indian jujube cultivars are introduced by Pawlowska *et al.* (2009). Grading standards for the fruit are shown in Tables 13.2 and 13.3.

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Table 13.1 Nutrition content of Chinese jujube and Indian jujube

Component	*Chinese jujube*						*Indian jujube*
	Jinsixiaozao	Yazao	Jianzao	Junzao	Sanbianhongzao	Dongzao	*Ziziphus jujuba* Lam.
Appearance	Red	Red	Red	Red	Red	Red	Greenish yellow
Carbohydrate (mg100 g^{-1} ·DW)	81.62	80.86	84.85	82.17	85.63	–	18.0–23.0
Reducing sugar (mg/100 g^{-1} ·DW)	57.61	60.24	77.93	58.73	67.32	7.88	1.4–6.2
Soluble fibre (mg1001g·DW)	2.79	1.46	1.51	1.07	0.57	1.37	0.60
Insoluble fibre (mg100 g^{-1}·DW)	6.11	7.18	5.24	5.83	5.56	–	–
Lipid (mg100^{-1}g·DW)	0.37	1.02	0.39	0.71	0.65	–	1.25
Protein (mg100 g^{-1}·DW)	5.01	6.86	4.75	6.43	6.60	0.307	2.63
Moisture (mg100 g^{-1}·DW)	18.99	20.98	17.38	21.09	22.52	74.08	81.6–83
Ash (mg100 g^{-1}·DW)	2.26	2.78	2.41	3.01	2.56	–	5.83
Potassium (mg100 g^{-1}·FW)	79.20	458.00	375.00	201.00	244.00	298.00	0.47–1.57
Phosphorus (mg100 g^{-1}·FW)	110.00	59.30	72.30	105.00	79.70	34.20	26.80
Calcium (mg100 g^{-1}·FW)	65.20	91.0	45.6	118	76.9	15.2	25.60
Manganese (mg100 g^{-1}·FW)	39.70	36.50	51.20	24.60	42.10	0.16	0.30
Iron (mg100 g^{-1}·FW)	4.68	6.93	6.42	7.90	6.01	1.99	0.76–1.80

(Continued)

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Table 13.1 Continued

Component	Chinese jujube						Indian jujube
	Jinsixiaozao	Yazao	Jianzao	Junzao	Sanbianhongzao	Dongzao	*Ziziphus jujuba* Lam.
Sodium (mg100 $g^{-1}\cdot$FW)	6.34	7.61	6.21	5.96	3.22	15.2	0.02–0.05
Zinc (mg 100 $g^{-1}\cdot$FW)	0.55	0.63	0.47	0.42	0.35	0.16	3.00
Copper (mg 100 $g^{-1}\cdot$FW)	0.26	0.27	0.42	0.31	0.19	0.07	0.80
Thiamine (mg 100 $g^{-1}\cdot$FW)	0.05	0.04	0.09	0.06	0.05	–	0.016
Riboflavin (mg 100 $g^{-1}\cdot$FW)	0.07	0.07	0.05	0.09	0.05	–	0.024
Vitamin C (mg 100 $g^{-1}\cdot$FW)	359.00	192.00	203.00	296.00	315.00	379.40	280.00
Phenolic content GAE (mg g^{-1})	7.42	8.53	8.36	7.01	5.18	–	–
Antioxidant capacity FRAPA (μmol g^{-1})	1173.00	1025.00	794.00	563.00	342.00	–	–

Sources: Li *et al.*, 2007; Sheng *et al.*, 2003; Xu and Wu, 2009; He *et al.*, 2002

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Table 13.2 Grading standard for dry red jujube (Zhang and Li, 2007) with permission of the authors

Grade	Shape and size	Quality	Mechanical injury and blemish	Moisture content
Top	Uniform size (≤300 fruits per kg) and shape, owned cultivar characters	Plump flesh, bright red, dryness, impurity ≤0.5%	No mildewed, serous part, immature, diseased and wormy fruits, skin crack and oiled skin spot fruit ≤3%.	≤28% of *Ziziphus jujuba* Mill. cv. Jinsixiaozao
1	Uniform size (≤360 fruits per kg) and shape, owned cultivar characters	Plump flesh, bright red, dryness, impurity ≤0.5%	No mildewed, serous part, immature and diseased fruits. Skin crack, oiled skin spot or wormy fruit ≤5%.	≤28% of *Ziziphus jujuba* Mill. cv. Jinsixiaozao
2	Uniform size (≤420 fruits per kg) and shape, owned cultivar characters	Plump flesh, bright red, dryness, impurity ≤0.5%	No mildewed and serous part fruits. Diseased, wormy, skin crack, oiled skin spot or dried immature fruit ≤10% and diseased and wormy fruit ≤5%	≤28% of *Ziziphus jujuba* Mill. cv. Jinsixiaozao
3	Fruit with normal shape and cultivar characters	Fruit flesh uneven, fruit with uneven bright red ≤10%, dryness, impurity ≤0.5%	No mildewed fruit, serous part, diseased, skin crack, oiled skin spot or dried immature fruit ≤15% and diseased and wormy fruit ≤5%	≤28% of *Ziziphus jujuba* Mill. cv. Jinsixiaozao

Table 13.3 Grading standard for Dongzao jujube (Zhang and Li, 2007) with permission of the authors

Grade	1	2	3
Weight	≥20 g per fruit	16~20 g per fruit	10~16 g per fruit
Shape	Nearly spherical and uniform	Nearly spherical and uniform	Nearly spherical
Defects	No	No disease and pest fruit, crevasse fruit ≤3%	No disease and pest fruit, crevasse fruit ≤5%
Color	Red and brightness, tinctorial area >30%	Red and brightness, tinctorial area >30%	Red and brightness, tinctorial area >30%
Taste	Crisp, tender and juicy, sweet and acidulous, delicious, no residue	Crisp, tender and juicy, sweet and acidulous, delicious, no residue	Crisp, juicy, sweet and acidulous, delicious, no residue

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13.2 Ripening behavior and postharvest physiology

13.2.1 Ripening behavior

During the growth and development process, a series of changes take place in the size, shape and color of jujube fruit. For Chinese jujube, most varieties mature from middle-late September to early October. The stages of Chinese jujube maturity can be divided into the white maturity stage, crisp ripe stage and the ripening stage (Geng, 1995), as described below.

The white maturity stage is characterized by the fruit having an essentially fixed size and shape. In this mature stage, the green peel color subsides, and the fruit takes on a green-white or milky-white color. The flesh of the fruit is soft, and the fruit juice and sugar content are low. Therefore, the jujube in the white maturity stage is suitable for processing into preserved fruit.

The crisp ripe stage is characterized by a half-red or wholly-red fruit, a crisp flesh texture, higher juice levels, and a sharp increase in sugar content. Fruit at this stage is used for making fresh cookies and is processed into wine.

The ripening stage is characterized by a more deeply-red pericarp and yellowish-brown flesh which adheres closely to the nucleus. As jujube fruit at this stage is fully mature, its products have a high dry weight, a heavy and dark color, a full and flexible pulp, and are of good quality for eating.

For each cultivar, the requirements for fruit growth and development can be calculated in terms of degree-days. In general, the harvest period in northern India is mid-February to March for cultivar ‘Gola’, mid-March to the last week of March for cultivar ‘Kaithli’, and March to April for cultivar ‘Umran’. The periods of availability of jujube fruits in India vary from December to March, depending on climatic conditions. Therefore, the degree-days required for maturity should be computed for different regions (Pawlowska *et al.*, 2009). The best time for eating fresh is when the fruit is red; if the color becomes dark red, the fruit may be overripe and susceptible to decay.

13.2.2 Ethylene and CO_2 evolution rates

The various *Z. jujuba* cultivars may differ in their patterns of respiration and ethylene production. The storage life of Chinese jujube is primarily related to the fruit respiration rate, and does not correlate closely with the ethylene production rate (Kader *et al.*, 1982). Some cultivars such as ‘Dazao’ and ‘Yuanzao’ are considered to be non-climacteric (Kader *et al.*, 1982; Lu *et al.*, 1993). Shen *et al.* (2004) reported that the respiration rate and ethylene production of ‘Dongzao’ jujube at 4°C and 20°C each exhibited increasing tendencies with extension of storage time, but that no apparent peaks of respiration or ethylene production were detected. This suggests that ‘Dongzao’ jujube fruit is non-climacteric. In contrast, Jiang and Sheng (2003) found that the rates of respiration and ethylene production of ‘Jins’ jujube during storage initially increased, then reached respective peaks before finally decreasing rapidly, and were further promoted when the fruit was exposed to ethylene. These observations suggest that ‘Jins’ cv.

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is climacteric. At present, researchers have diverse opinions regarding the patterns of respiration and ethylene production which differ among the various cultivars of Chinese jujube.

Pawlowska *et al.* (2009) found that Indian jujube fruit has a high respiration rate and a climacteric respiration pattern, and reaches its prime eating quality at the climacteric peak. They also reported that jujube fruit produces high amounts of ethylene and responds to exogenous ethylene treatment as measured by changes in skin color, juice color and composition. Cultivar 'Zaytoni' is classed as climacteric on the basis of its respiration rate and ethylene production during postharvest periods, with the peaks of CO_2 and ethylene production occurring simultaneously (Muay'ed *et al.*, 2002) In the 'Kaithli', 'Rashmi', 'Umran', 'Ponda' and 'ZG-3' cultivars, the rate of respiration increases gradually and reaches its peak when the fruits have attained a chocolate-tinged color, indicating the late-peaking climacteric nature of these fruits.

13.2.3 Treatments to reduce respiration and ethylene rates

Keeping a low rate of respiration rate and ethylene production is key to securing long shelf-life of *Chinese jujube* and *Indian jujube* fruit. The main methods used commercially are as follows.

Low temperature

Temperature is the most important environmental factor affecting respiration and ethylene production rates of jujube fruits. Research by Qu (1985) suggests that storage effects and temperature have a close relationship. Temperature directly affects the respiration rate; hence, proper temperature control to suppress the metabolic activity of fruits is the most basic requirement for storage of jujube fruit. Furthermore, Wu *et al.* (2001) have shown that low temperature can suppress Chinese jujube fruit respiration and maintain low-level metabolism; jujube fruit at room temperature (20°C) has a high respiration rate, while at 0°C the respiration rate is low, and the respiration rate on the seventh day is only 3.5% of that of the first day.

Low pressure

Wang *et al*. (2003) found that low-pressure storage led to a slowing down of respiration in jujube fruit, and inhibited ascorbic acid oxidase (AAO) activity. Under these low pressure conditions, loss of hardness and color changes in the fresh fruit were also significantly inhibited.

1-Methylcyclopropene (1-MCP)

Ethylene plays an important role in ripening and senescence of various fruits, vegetables and flowers (Abeles *et al.*, 1992). The compound 1-MCP is a highly promising compound among several recently developed inhibitors of ethylene actions, and has been shown to prevent ethylene-induced effects in various ornamentals, fruits and vegetables (Serek *et al.*, 1995; Sisler and Serek, 1997; Fan and Mattheis, 2000).

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Jiang and Sheng (2003) found that jujube fruit ripening was significantly inhibited by 1-MCP. Unlike the control (fruit not exposed to 1-MCP), Chinese jujube fruit treated with 1-MCP did not exhibit a significant climacteric dependency in terms of respiration and ethylene production. In addition, the effects of exogenous ethylene on fruit ripening of 'Jins' cv. were also effectively overcome by 1-MCP treatment.

Storage of 'Dongzao and the effects of 1-MCP treatment on jujube fruit quality during storage were also studied by Sheng et al. (2003) who found that 1-MCP did not alter the trends in ethylene production or respiration rate, but did significantly reduce the total amount of ethylene production and the respiration rate.

Gibberellic acid (GA)

Compared with the actions of ethylene, GA is known to be effective in retarding leaf senescence, chlorophyll loss of citrus fruit peel and softening of peaches (Martinez, 2000). It is not known how GA regulates ripening of jujube fruit. However, Jiang and Sheng (2003) found that GA delayed the decreases in firmness and ascorbic acid levels, and reduced the level of ethanol. Furthermore, it was observed that the combination of GA + 1-MCP yielded additional beneficial effects in inhibiting ripening of the Chinese jujube. Liu (2009) also found that GA treatment delayed the rapid accumulation of malondialdehyde (MDA) and damage to the membrane system in Zhongning yuan zao jujube (Liu, 2009).

Nitric oxide (NO)

There is increasing evidence that NO can react with metal ions or sulphydryl groups in proteins (David *et al.*, 2005; Koppenol, 1998). As a signal transmitter of cells, NO can not only play an important role in the physiology, biochemistry, pathology and pharmacology of the circulatory, respiratory, digestive, endocrine, nervous and immune system in humans and animals, but can also regulate the processes of growth, disease resistance and stress tolerance in plants. Exogenous NO treatment can postpone ripening and senescence and prolong the storage life of horticultural products such as strawberry and green pepper (Zhu *el al.*, 2005; Cheng *et al.*, 2005). Sun and Liu (2007) found that 20 $pL.L^{-1}$ NO could mitigate the injurious effects of ethanol on 'Dongzao' and effectively delay the browning and softening of fruits during storage.

Calcium

Calcium ions can help maintain the structure and function of cell walls, which affects fruit hardness. Treatment with exogenous calcium can increase the calcium levels in fruit, decrease the respiration rate and polymethylgalacturonase (PG) activity, and reduce ethylene production and pectin degradation. As a result, it can help maintain fruit hardness, reduce the incidence of disease in storage, and finally, delay senescence after harvest, as is the case in 'Dongzao' fruit (Chen, 1984; Wu *et al.*, 2001). Further information on calcium treatments can be found in section 13.5.2 and section 13.6.4.

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13.2.4 Artificial ripening

Jiang and Sheng (2003) found that the firmness of jujube fruit decreased significantly with exposure to an increasing ethylene concentration from 0 to 10 μl L^{-1}, while the level of soluble solids increased. This result suggests that ripening of jujube fruit was enhanced by ethylene. Furthermore, Yu (1997) found that ethephon treatment could promote the ripening of fresh jujube fruit, enhancing formation of the red color and improving the fruit quality. The content of ascorbic acid and sugar was found to be increased, while that of other acids was decreased. Abbas (1994) also found that ethephon treatment (500 μL.L^{-1}) could advance green jujube maturity by increasing the TSS and ascorbic acid content, and reducing TA content. Currently, ethylene or ethephon are used for artificial ripening of some fruits, and as long as the amounts used are controlled within the safe maximum levels of the states' standard guidelines, ethylene is safe for consumers.

Abscisic acid (ABA) is one of the main factors causing softness and senescence of jujubes, and increased ABA content can decrease the sucrose content and speed up fruit senescence (Zhang, 2000). Compared to control, ABA was found to increase the rate of production of superoxide anion in 'Dongzao' jujube during storage, promote the accumulation of MDA and H_2O_2, hasten the activity peaks of catalase (CAT), polyphenol oxidase (PPO) and peroxidase (POD), increase AAO activity and sharply decrease the total phenol content. Treatment of 'Lizao' jujube with indole-3-acetic acid (IAA), ethephon, and ABA enhanced ethylene production in the initial stages after harvest, increased the MDA content and lipoxygenase (LOX) activity, accelerated the softening, and decreased the ascorbic acid content and sound fruit rate. The effects of ABA were particularly marked (Yan, 2004).

13.3 Postharvest pathology and entomology

13.3.1 An introduction to postharvest pathology

Postharvest pathology is one of the most important factors affecting the commercial value of jujube fruit. About 80% of jujube fruit develop disease when stored at room temperature for approximately 10 days, but this would generally take two months when storage is at low temperature (4°C). The pathogens isolated and identified on jujube fruit by different researchers vary, as do the pathogens isolated and identified at different times from different regions, and from jujube fruit gardens with different ecotypes (Table 13.4) (Wei, 2006). One disease is also often caused by a mixture of a variety of different infections. During packaging, storage and transport, fruit may be exposed to various decay-causing microflora. Some of the predominant organisms observed on freshly harvested fruit are *Aspergillus niger*, *A. sydowii*, *Rhizopus oryzae*, *Penicillium chrysogenum*, *Alternaria tenisima*, *Phoma* spp., and *Cuvrularia* spp., of which *A. niger* and*R. oryzae* cause the greatest spoilage *in vitro* (Kainsa, 1978). About 16 fungi belonging to 12 genera have been reported to cause postharvest decay in jujube fruit, transit and storage. However, the names of some of the diseases affecting jujube fruit post harvest are based primarily upon the

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Table 13.4 List of diseases of jujube fruit

Name	Pathogens	Distribution and harmful degree	References
Anthracnose of jujube	*Colletotrichum gloeosporioides* Pens	Henan, Shandong, Shanxi, Hebei	Sun Yongan *et al.* (1984)
Jujube fruit shrink disease	*Eruinia jujubovra* Wang Cai Feng et Gao; *Dothiorellu gregaria* Sacc; *Coniothyrium olivaceum* Bon; *Alternaria alternata* f.sp. tenuis	Henan, Hebei, Shandong, Shanxi, Beijing and Anhui, the rot rate is 30% to 50%, the most severe areas have almost total crop failure	Chen Yijin *et al.* (1989); Qu Jianxu, *et al.* (1992); Li Zhiqing *et al.* (1997); Zheng Xiaolian *et al.* (1995, 1996)
Jujube brown cortex disease (brown cortex and shrunken fruit type)	*Alternaria alternate* (Fr.) Keissler; *Phoma destructiva* Plowr; *Fusicoccum* sp.	Henan, Hebei, Shandong, Shanxi, Beijing and Anhui, the rot rate is 30% to 50%, the most severe areas have almost total crop failure	Kang Shaolan *et al.* (1998)
Black-red spot disease of jujube	*Alternaria tenuis*; *Phoma* sp.	Taiyuan and Jiaocheng in Shanxi, and other places, 10% to 15% loss	Lin Zhongmin *et al.* (2001)
Rot fruit of *Zizyphus jujuba* Mill. cv. Dongzao disease; Black spot type; Canker, soft-rot type; Black spot disease of Dongzao	*Alternaria* sp.; *Alternaria tenuissima*; *Erwinia* sp.; *Pseudomonas* sp.; *Xanthomonas* sp.	Main producing areas of jujube in Lubei of Shandong, 66.7% loss	Xin Yucheng *et al.* (2003); Ji Yanping *et al.* (2003); Li Xiaojun *et al.* (2004)
Ring spot of jujube	*Macrophoma kawatsukai* Hara	In the north and Huanghua, Hebei, Henan and other places, 10% to 20% of fruit are affected, 40% to 50% in rainy years, the most severe areas have almost total crop failure	Chang Jupu (2004)
Thick rotten disease of Jinsixiaozao; Dark furuncle disease of Jinsixiaozao; Brown ring disease of Jinsixiaozao	*Macrophoma kawatsukai* Hara; Physalospora obtuse (Schw.) Cooke; *Fusicoccum* sp.; *Alternaria alternata* (Fr..) Keissler; *Phoma destructiva* Plowr	Hebei, Shandong, Tianjin, the rot rate is about 30%, the most severe area have almost total crop failure	Su Anren *et al.* (1994); Liu Chunqin *et al.* (2004); Zhang Lizhen *et al.* (2004)

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Table 13.4 Continued

Name	Pathogens	Distribution and harmful degree	References
Black rot disease of *Zizyphus jujuba* Mill. cv. Dongzao	*Alternaria alternata* (Fr.) *Keissler*; *Phoma aestructiva* Plowr; *Fusicoccum* sp.	Similar to fruit shrink disease, causing rot in post-harvest storage	Sheng Jiping *et al.* (2003)
Thick liquid disease; Mould rot disease; Foot rot of fruit stem	*Rhizomorpha* Roth.; *Alternaria* Ness.; *Rhizopus* sp.; *Mucor* sp.;	Hebei, Shandong, Tianjin, the rate of rot is about 20% to 40% after stored for 60 days	Wu Xingmei *et al.* (2003)
Soft-rot disease of jujube; Aspergillosis; Blue mold of jujube; Trichoderma disease of jujube	*Rhizopus* sp.; *Aspergillus* sp.; *Penicillium* sp.; *Trichoderma* sp.	Henan, Anhui, Hebei and Shaanxi, taking place in the harvesting, storage and processing period	Ren Guolan *et al.* (2004)
Other disease	*Botrytis* sp.; *Penicillium* sp.; *Phyllosticta* sp.; *Alternaria* sp.; *Aspergillus* sp.; *Bispora* or *Dicoccum* sp.	Taking place in the storage period	Zhao Jialu *et al.* (2002); Hao Lin *et al.* (2000)

symptoms of infected jujube fruit, and have both an alias and a common name. There are also different types of some diseases. All of these factors result in confusion. For example, jujube fruit shrink disease is also known as jujube brown cortex disease, black rot and brown rot; furthermore, black rot is also known as brown spot. Jujube brown cortex disease can be further divided into brown pericarp and fruit shrink diseases. *Z. jujuba* fruit rot disease can also be divided into black spot, canker and soft-rot type. The diseases caused by pathogenic organisms are mainly thick liquid disease and stem end rot disease (Wu, 2003).

Jujube fruit shrink disease

Jujube fruit shrink disease, which as mentioned above is also known as brown cortex and black rot disease, is the most serious of the jujube diseases. This disease is initiated in the jujube white maturity period, causing flesh browning, a bitter taste and early fruit drop, resulting in a decreased yield and quality. This disease is mainly caused by fungi and bacteria singly or jointly (Wu, 2003).

Thick liquid disease

Thick liquid disease is caused by *Rhizomorpha Roth.* and *Alternaria Nees ex wallr*. The symptoms are firstly a pale skin, and dark red and dark brown

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discoloration spots in the shoulder or waist of the fruit. The color also deepens, the texture of the skin changes, the flesh provides no resistance to touch and the inside of the fruit becomes a pulp slurry. Finally, the severe lesions make the entire fruit rot. It is a particularly serious disease in later stages of storage (Wu, 2003).

Foot rot of the fruit stem

Foot rot of the fruit stem is caused by a mixed infection. The pathogenic organisms are the root *Rhizomorpha Roth. ex Fr.*, *Rhizopus, Alternaria* and *Penicillium*. Foot rot of the fruit stem begins from the base of stem. According to the color, the disease can be divided into water-rotten type, brown rot type and black rot type. The water-rotten-type lesion exhibits light brown or watery spots, and soon the entire fruit rots. As the name suggests, the brown rot-type lesion is brown, and rotting is faster than with the water-rotten-type lesion. The black rot-type lesion is black and results in the slowest rotting rate. Thick liquid disease and foot rot of the fruit stem are the most severe diseases during storage (Wu, 2003).

13.3.2 Control of postharvest pathology

Physical control and chemical control

Physical control measures commonly include low-temperature storage, controlled atmosphere (CA) storage, vacuum storage and heat treatment. Common chemical control measures include dipping with fungicides. Lal (1981) evaluated five fungicides and found that Bavistin and Difolation performed best and could be recommended as fruit dips at 500 ppm and 1000 ppm, respectively. Treatment with 1% Bavistin and 5% Virosil reduced both pathological and physiological losses in ambient conditions (30°C) as well as in cold storage (7°C) (Vishal, 1999). Fungal infections on stored ‘Gola’ fruit caused by pathogens such as *Rhizopus sexualis*, *R. microperum* and *R. oligosporu*s, as well as *Mucerpyriformis*, *Alternaria alternata*, *A. niger*, *A. fiavus*, *Trichothecium roseum*, *Tridadium splendens*, *Phoma scrghuia*, *Fusarium culminorum* and *Penicillium* spp. were suppressed when jujube fruits were stored at low temperature (7°C) after treatment with cold water (30 min, 0°C), hot water (50°C for 5 min), and 0.5% calcium chloride. There was a significant decrease in the infection rate (a reduction of 93.3%) in fruit stored at room temperature (28 ± 2°C) after treatment with cold water (15 min, 0°C), hot water (5 min, 50°C), 2,500 ppm Virosil and 0.5% calcium nitrate (Nallathambi, 2000). Further information about treatments that influence levels of postharvest disease as well as other factors related to postharvest quality, such as rate of ripening, can be found in section 13.6.

Biological control

Biological control of plant diseases relies on the use of appropriate antagonists. Most antagonists which have a significant inhibitory effect on pathogenic fungi can be isolated from bacteria, fungi and yeast in plants and soil. The mechanism of biological control by antagonists is considered to be that antagonists compete with the pathogens for nutrition and space, or that the antagonists induce host

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resistance. Strain B501 isolated by Xue *et al.* (2008) from the surface of jujube fruit showed antagonistic activity on jujube fruit against black spot disease caused by *Alternaria alternata*. This bacterium was identified as *Pantoea agglomerans* according to its physiological and biochemical properties, and from phylogenetic analysis of its 16S rDNA sequence. Strain B501 could noticeably and significantly reduce the incidence of black spot when applied on wounded fruits at the relatively low concentration of 1×10^7 cfu/ml, with a success rate of 80%.

13.3.3 Postharvest entomology

At present, there are more than 42 major harmful insect pests found in *Ziziphus* fruit, with losses caused by insects in the storage of dry fruit more serious than that in fresh jujube storage. The serious pests are *Lygus lucorum* Meyer-Dur, *Eriophyes annultus* Nale, *Contarinia* SP, *Tetranychus truncatus* Ehara and *Europhera batanyensis* Cara-dja. There are economic, security and environmental advantages to the use of biological controls to inhibit insect pests, which makes them a suitable prospect for use on jujube. It has been found that the nuclear polyhedrosis virus of *Sucra jujuba* Chu has particularly inhibitory effects (Ji and Liu, 2000).

13.4 Postharvest disorders

Postharvest disorders of jujube include alcoholic fermentation, browning and chilling injury. Shen *et al.* (2004) investigated the process of fermentation softening in Dongzao jujube fruit. The results showed that the ethanol content increased linearly during storage. When the ethanol content reached $0.1\,g\cdot100\,g^{-1}$ formula weight (FW), fermentation softening took place, with over-accumulation of ethanol being the main reason for softening. Fumigation of fruits for 12 h at room temperature with 1-MCP at 1.0 $\mu L\cdot L^{-1}$ inhibited ethylene production and delayed the progress of fermentation and softening.

Wu *et al.* (2001) examined the relationship between softening, browning and polygalacturonase (PG) and PPO activity, as well as the effects of preharvest treatment with $CaCl_2$ and 6-BA solution on softening, browning and PG and PPO activity, in postharvest 'Zanhuang' jujube. During storage periods, PG activity fluctuated and showed little correlation with softening, while the browning index and PPO activity increased, with PPO activity showing a relationship with flesh browning. With preharvest treatment of 1% $CaCl_2$ or 1% $CaCl_2$+15 mg/kg 6-BA, at the last stage of storage the flesh firmness of 'Zanhuang' jujube was improved by 1.2 kg cm^{-2} or 1.5 kg cm^{-2}, respectively, relative to control.

Jujube fruit is also susceptible to chilling injury when exposed to temperatures below freezing. Wang *et al.* (2007) reported that the freezing temperature of 'Langzao' in the half-red stage is −2.4°C ~ −3.8°C, while 'Lizao' is susceptible to freezing injury when exposed to −2°C over a long period. Chilling injury is characterized by the appearance of pits on the fruit peel as a result of damage to plasma membranes and loss of cellular integrity.

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13.5 Preharvest treatments to extend shelf life

Preharvest treatments have important effects on the shelf life of jujube fruits, and appropriate treatment before harvest will distinctly extend the fruit shelf life. There are many available methods to extend the shelf life of jujube fruits, such as choosing the optimal harvest maturity, calcium treatment and bagging on the tree.

13.5.1 Varieties and harvest maturity

The choice of jujube cultivar affects postharvest fruit quality. Wei and Li (2009) investigated the effects of variety on the quality of fruits of Chinese jujube. Flesh firmness and the contents of ascorbic acid, soluble solids, sucrose and total sugars in 'Liwuchangzao', 'Dongzao' and 'Lizao' harvested at the same time decreased after 95 days of cold storage. Of the three varieties, after storage the flesh firmness and ascorbic acid content were lowest in 'Lizao', while the sucrose content in 'Dongzao' was reduced by 88.5%, which represented the greatest reduction of the three varieties. The contents of titrable acidity in 'Lingwuchangzao' and 'Dongzao' showed an upward trend, but there was a downward trend in 'Lizao'. The fructose content of 'Dongzao' rose sharply by 113.6%, resulting in 'Dongzao' becoming sweeter than 'Lingwuchangzao' and 'Lizao' after storage.

Jujube fruits that are allowed to ripen on the tree normally have a shorter shelf-life, and the best results have been obtained when fruit are picked before the onset of ripening. The development of fruit skin color is one of the most reliable maturity indices. Fruit are harvested at the mature golden-yellow stage for the 'Umran' and 'Kaithli' cultivars, and at the mature green stage for the 'Mallaey' and 'Bambadawi' cultivars (Pareek *et al.*, 2009).

Wei and Li (2009) also investigated the impact of harvest timing on 'Liwuchangzao' cv. quality, and the changes in jujube quality before and after storage. The results showed that the flesh firmness of fully red fruit flesh was less than that of half-red fruit of 'Lingwuchangzao' cv. harvested on a different date. The half-red fruit have a longer shelf life. Han *et al.* (2008) studied the differences in respiration, cell membrane permeability and weigh loss ratio in 'Lingwuchangzao' harvested at the three harvest maturity, fumigated with thiabendazole (TBZ) at 20±0.5°C and stored at −0.5±0.5°C. They reported that the low-maturity grade had better storage properties, but lower quality. Every physiological index of jujube fruit showed an increase after fumigation. Overall, with regard to storage properties and quality, the low maturity degree was considered to be the best harvest maturity, under proper storage conditions.

13.5.2 Calcium treatment

The calcium content of fruit influences the shelf life. Therefore, preharvest applications of calcium compounds can have an effect on storage life. Fruits naturally contain calcium as compounds of pectate, carbonate, oxalate and phosphate. Shi *et al.* (2004) analyzed the effects of calcium on fruit ripening and senescence, of 'Dongzao' 'Dongzao' were treated with 0.2% calcium chloride as a spray five

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times before harvest. The protein content of calcium-treated fruit was significantly higher than that of non-treated fruit. Some important antioxidant enzymes which can eliminate free radicals, reduce the damage to the membrane system and delay the aging process in plants were also detected in this experiment. The results showed that LOX activity decreased but superoxide dismutase (SOD), POD and PPO activity increased from the white maturing to the half-red period. This showed that calcium treatment before harvest had a positive anti-senescent effect on the postharvest 'Dongzao' fruit. Xing *et al.* (2009) also reported that three different calcium solutions sprayed three times on the surfaces of 'Dongzao' fruit during the early stages of fruit growth could remarkably retard the increase in browning index, prolong the shelf-life and reduce loss of fruit firmness.

Spraying ber fruits 10 days before harvest with $CaCl_2$ ($1.7\,g\ L^{-1}$) with 1% Teepol as a surfactant reduced fruit weight loss, delayed color development and resulted in maintenance of quality during storage (Pareek *et al.*, 2009). In another study, a reduced respiration rate was associated with increased calcium content arising from exogenous application of calcium nitrate (Gupta and Mehta, 1988). Spraying with 1% $CaNO_3$ at the color-turning stage was also found to improve the shelf-life of fruit at room temperature (Siddiqui *et al.*, 1989).

13.5.3 Bagging

Bagging on the tree has been widely used and is an effective way to improve the postharvest quality of fruit. Bagging can promote anthocyanin synthesis and improve fruit coloration, reduce pest infestation, and maintain the smoothness of the fruit surface. Li *et al.* (2008) studied the effects of preharvest bagging on the postharvest storage properties of 'Lizao' jujube, and showed that the respiration rate of bagged jujube fruit was lower than that of the control fruit. PG activity showed little correlation with softening. The curve of POD activity showed two peaks, with the second higher than the first, while the activity curve of PPO during storage showed a single peak. Relative to control, the activities of PG and POD in bagged jujube fruit were inhibited and the POD peaks were delayed. Flesh firmness was also retained at a higher level in the bagged fruit and the rate of decay was reduced.

13.6 Postharvest treatments to extend shelf life

This section examines the effects of postharvest treatments on fruit quality.

13.6.1 Low-temperature storage

Temperature is one of the most important factors affecting the storage life of fresh jujube fruit. Cold storage of fruit has advanced noticeably in recent years, leading to better maintenance of organoleptic qualities, reduced spoilage and longer shelf-life. To a certain extent, the lower the temperature, the better the storage. To avoid chilling injury, the cold storage temperature of most varieties of fresh jujubes

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should be controlled at −0.5°C ~ 1°C, and the respiration rate of the fruit should be controlled at a very low level. Several studies have examined the effect of low temperature on postharvest changes in the chemical constituents of jujube fruits, and on their storage behavior. Storage at temperatures around 0°C inhibited the jujube respiration rate, helped maintain a fresh state, and preserved ascorbic acid contents (Chen and Wang, 1983). Use of low temperatures (0°C) can slightly restrain PG and pectin methylesterase (PE) activity in the earlier stages of fruit maturity, preserve SOD and POD activity, and reduce the rise in malondialdehyde (MDA) activity (Wu, 2001). Zhai *et al.* (2008) studied the changes in quality during the different stages of maturity of 'Xinjiang Dongzao' jujube fruit in storage. The results showed that using a preserving agent and packing in micro-porous preservative film, then storing at (−2 ± 0.5)°C, is an effective way to improve the quality of 'Dongzao' jujube. Jawanda *et al.* (1980) observed that 'Umran' and 'Sanaur' fruit could be stored at −2°C in commercial cold storage for up to 30 and 40 days, respectively. Tembo *et al.* (2008) reported that jujube fruits stored at low temperature (5°C) lost only 48% of their weight during the entire 12-week storage period, while fruit stored at ambient temperature (22°C) and intermediate temperature (15°C) lost 70 and 75% of their weight, respectively. After three weeks of storage, more than 40% of the fruit at the ambient and intermediate storage temperatures had shriveled, compared to only 3% at the low storage temperature. It can be concluded that cold storage conditions can help reduce the respiration rate and ethylene production of fruit, maintain firmness and POD and CAT activity, and can retard weight loss, rises in MDA content and membrane permeability, prolonging shelf life. In cold storage (10°C, 79% relative humidity (RH)), fruit of the 'Gola', 'Kaithii' and 'Umran' cultivars remained acceptable for up to 42, 28 and 35 days, respectively (Pareek *et al.*, 2009).

13.6.2 Controlled atmosphere (CA)

Treating 'Dongzao' with 20 $\mu L\ L^{-1}$ NO can mitigate the injurious effects of ethanol and effectively delay the browning and softening of fruit during storage (Sun, 2007). Treatment with 20 $\mu L\ L^{-1}$ NO was also found to significantly slow the increase in red index, inhibit changes in PPO and phenylalanine ammonialyase (PAL) activities, help maintain a low total anthocyanin content and a high total phenol content, and delay the increase in soluble solids and decrease in ascorbic acid (Zhu, 2009).

Compared to storage in air, the contents of ethanol and ethyl acetate, and the degradation of anthocyanin and chlorophyll, were significantly lower in fruit stored in 5% O_2 + 0% CO_2 or 10% O_2 + 0% CO_2 at −1 °C. In comparison to other treatments, short-term high O_2 (70%) treatment was the most effective in maintaining peel color and anthocyanin and chlorophyll contents, and preventing peel browning. The ethanol content was significantly lower in the fruits stored in CA with 10% O_2 + 0% CO_2, relative to storage in air, while storage in 5% O_2 + 0% CO_2 was effective in reducing the ethyl acetate content throughout the storage

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period. The use of CA conditions effectively controlled disease development of the jujube fruit, while soluble solid contents (SSC) and TA were not significantly affected by CA treatments (Lin, 2004). The membrane permeability of jujube fruit was kept in a relatively controlled state by CA (12–15% O_2 + 0% CO_2), and the increase in alcohol content was also retarded. The browning and fermentation of jujube could also be inhibited by appropriate CA conditions (Zong, 2005).

A CA index of 2% O_2 + 0% CO_2 was the most beneficial during storage of 'Dongzao'. Using an appropriately low level of O_2, it was possible to restrict the decrease in pulp hardness, maintain cell membrane integrity and reduce acsorbic acid losses, while this did not cause a great accumulation of ethanol and acetaldehyde (Wang, 2008). Use of an appropriately low concentration of O_2 for 'Dongzao' could also reduce the respiration rate, slow down the increase in the relative electrical conductivity of the pulp, restrict the reduction in relative pulp firmness, delay the degradation of ascorbic acid, and maintain general fruit quality during storage (Wang, 2009). Compared with low temperature storage in air, CA with 10% O_2 plus 0% CO_2 significantly reduced the softening rate and maintained fruit firmness and total soluble sugar (TSS) and TA content during the entire storage period. Moreover, in fruits stored in CA a relatively greater abundance of esterified pectins and lignin-like phenols was found in the flesh cell wall, with less linear long-chain aliphatic compounds in the cuticle layer (Wu, 2009).

13.6.3 Ozone application

The application of ozone in storage of 'Dongzao' can inhibit microbial growth, reduce fruit respiration and ethylene levels, prevent browning and delay metabolic processes (Liu and Wang, 2004). These researchers also found that starch content and amylase activity were lower in jujube treated with ozone. Wet storage of the jujube combined with ozone at low temperatures could effectively inhibit LOX and POD activity, and delay the decline of SOD activity and rise in MDA activity, which helps to maintain the integrity of the cell membrane.

Treatment of 'Lingwuchangzao' with 100 $\mu g \cdot L^{-1}$ ozone could remarkably mitigate the acid content changes, reduce the sugar content, and keep the ascorbic acid level. After 90 days storage, the percentage of hard fruit was 50% and that of acceptable fruit was 95.3% (Hang, 2007). Treatment with 0.75% chitosan coating and 300 μg/L ozone at room temperature could reduce losses of TSS, TA and ascorbic acid, postpone the decrease in sugar levels, and remarkably mitigate the decreases in phenol content. This treatment could also activate POD, which is a key component of the protective enzyme system.

Compared with control, ozone water treatment can help maintain fruit firmness of 'Dongzao' and inhibit changes in surface redness and ethanol accumulation, help maintain the TA and ascorbic acid content, delay senescence, and aid in maintenance of a better appearance and quality during storage. In these experiments, the best concentration of ozone water treatment was found to be 1.00–1.99 $mg.L^{-1}$ (Yang, 2009).

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13.6.4 Calcium solution treatment

Calcium plays an important role in postharvest physiological and biochemical and fruit storability. As already mentioned, exogenous calcium treatment can help to maintain fruit hardness, reduce disease, and delay ripening and fruit softening (Ferguson, 1995). Treatment with 2% $CaCl_2$ solution can significantly prolong the postharvest fruit storage period (Chen, 1984). Ca^{2+} treatment was found to regulate the physiological activity of jujube fruits, and prohibit the respiratory consumption of organic acid and the loss of ascorbic acid (Li, 2003). Vacuum infiltration of Ca^{2+} in 'Lingwuchangzao' can prevent the oxidization of ascorbic acid. By the sixtieth day of storage the percentage of acceptably fresh fruit in the treatment group was 90.9%, while that in the control group was 60.5%. However, the effects of vacuum-infiltration of Ca^{2+}or Ca^{2+} plus plant hormone on the flesh firmness and TA, SSC, total sugar and pectin levels were not significant. About 5% of jujube fruits were found to be cracked after infiltration with Ca^{2+} or Ca^{2+} plus plant hormone, thus affecting the appearance of the jujube (Wei, 2008).

13.6.5 Preservative treatments

Fumigation of *Z. jujuba* Mill cv. 'Lingwu Chang' with 5 g/m^3 4.5% TBZ, (−0.5 ± 0.5°C; RH 90 ± 3.0%) was found to remarkably mitigate against the changes in acid levels and the reduction in sugar levels (Zhao *et al.*, 2009).

Traditional Chinese herbs are widely used as safe preservatives. Gan *et al.* (2008) found that the optimal concentrations of preservatives for *Z. jujuba* Mill cv. 'Lingwu Chang' were 40 g L^{-1} ethanol extract of *Forsythia suspensa* (Thumb.) Vahl, 20 g/L water extract of *Alpinia officinarum* Hanc, 12 g L^{-1} ethanol extract of *Eugenia caryophyllata* (Thumb), 10 g L^{-1} $CaCl_2$, and 75 mg/kg GA_3. After 30 d storage at room temperature (18 ~ 22°C), the rate of decay was only 12.64%, the rate of softening was 1.83% and water loss was 1.82%. Meanwhile, the fruit quality was well maintained, with the fruit retaining its firmness and fine flavor after storage.

Some edible preservative agents for Chinese jujube have been developed. Dou *et al.* (2009) used sugar, ascorbic acid and citric acid to develop edible preservative agents for 'Dongzao', with both giving good results: Formula I with a 70% ethanol solution of a mixture of wax and lipid, and Formula II with a sugar, ascorbic acid and citric acid aqueous solution.

13.6.6 Chlorine dioxide treatment

The quality of 'Dongzao' has been shown to be enhanced by treatment with 80 mg.kg^{-1} chlorine dioxide, relative to control. After 80 days of storage, the percentage of sound 'Dongzao', the firmness, the ascorbic acid content, and the PG activity were found to be higher than those of the control, while soluble pectin levels and PPO activity were lower than those of the control (Zhang, 2008). These results showed that chlorine dioxide can be used to preserve 'Dongzao' quality.

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13.6.7 Ethanol treatment

Treatment with 4.5 mL.kg^{-1} ethanol can delay softening and the decline in ascorbic acid content, as well as decrease the rate of decay, and prolong the postharvest life (Li, 2006). Ethanol application is also reported to decrease the respiratory rate and ethylene production, preserve appearance, and delay senescence and ripening of jujube fruit (Li, 2008).

13.6.8 Irradiation

Irradiation treatment can prevent rot and extend jujube shelf life post-ripening (Liu, 1998), but the radiation dose and irradiation time are difficult to control, and therefore this method is not currently widely used. A 1 kGy dose gamma-ray irradiation of plastic film-packed dried *Z. jujuba* can effectively kill insects in the jujube, such as Lepidoptera or Elytrum. After one year of preservation, the sound fruit percentage of the irradiated jujube was found to be more than 90%. The levels of the major nutrients such as sugars, amino acids, vitamins and inorganic salts were apparently not altered (Liu, 1987). However, treating *Z. jujuba* with UV light irradiation for 15 min before storage, then packing with a small non-perforated thin-film package, or a large perforated thick-film package, in combination with the presence of permanganate in the package, was found to be ineffective in keeping jujube fresh (Xu *et al.*, 1996).

13.6.9 Hypobaric storage

Hypobaric storage of jujube fruit has been found to help maintain firmness and ascorbic acid content, reduce acetaldehyde and alcohol content in the pulp, lower the respiratory rate and ethylene production rate, and inhibit AAO and alcohol dehydrogenase (ADH) activities, although an effect of hypobaric storage on flesh browning was not apparent (Xue, 2003). Fruit stored under hypobaric conditions of 55.7 kPa showed the best quality (Jin, 2006). In comparison with the control, hypobaric storage of 'Dongzao' helped retain firmness and preserve the appearance, decrease weight loss, maintain the organic acid and ascorbic acid content, and retard senescence (Wang, 2007). Hypobaric storage decreased the respiration rate of 'Lizao', delayed the loss of fruit ascorbic acid content, decreased the rate of production of superoxide anion, clearly slowed down changes in redness, increased the percentage of sound fruit and to a certain extent prolonged the fruit storage life. There were no significant differences found in terms of the physiological and biochemical indexes of 'Lizao' between treatment under 20.3 kPa and 50.7 kPa (Cui, 2008).

13.6.10 Heat treatment

Treatment with hot water at 53°C for 6 minutes could help delay 'Dongzao' senescence, maintain the flavor, suppress physiological and pathological injury,

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and reduce decay and dehydration rate (Cao, 2007). Immersion of *Z. Mauritiana* fruit in hot water at 55°C for 10 minutes was also found to help maintain quality, and significantly inhibit decay and water loss, during storage (Yao, 2007).

13.6.11 Other treatments

The shelf-life of jujube fruit which was treated by microwave for 20~25 s was prolonged by 2~3 days. The rates of respiration, degradation of TSS, loss of organic acids (OA) and ascorbic acid, and water loss all decreased (Chen, 2008).

13.7 Postharvest handling

13.7.1 Storage at ambient temperature

After harvest, jujube fruit are usually stored at ambient temperature until they are either sold or processed. The fruit are often stored in heaps under shade or in storage rooms, but it is better to store them in packages such as gunny bags, net bags, polythene bags or boxes. Depending upon the cultivar and the storage conditions, fruit can be kept for 4 to 15 days without loss of organoleptic quality (Zhang and Li, 2007). During storage, the fruit lose weight and shrivel, change color from green-yellow or golden-yellow to reddish-brown and lose acidity and ascorbic acid, but gain in sweetness.

13.7.2 Grading

Jujube fruit is commonly harvested at different stages of maturity, and needs to be sorted into different groups before marketing, storage or processing. Fruit are sorted and graded according to maturity, size, shape and color. First the fruit are sorted by hand, and the under-ripe, over-ripe, damaged and misshapen fruit are removed. The under-ripe fruit are set aside and left to ripen, while over-ripe fruit, which are not desirable for the fresh market or for processing, are discarded. The remaining fruit are graded into two or three groups, based on the size and color. Grading can either be carried out manually or by passing the fruit through sieves of different mesh sizes (Zhang and Li, 2007). The grading standards for dry red jujube and 'Dongzao' jujube fruits are included in Table 13.2 and Table 13.3, respectively.

After grading, fruit destined for further processing are washed using chlorinated water (100 ppm) and drained. Fruit destined for sale are packed, and either stored or transported to the market.

13.7.3 Packaging

After harvest, the fruit are brought to the pack house or under shade for cleaning, packing, or for postharvest treatment to extend their shelf life. The fruit are packed either for controlled storage or for safe transport to local or distant markets.

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Correct and appropriate packaging of the fruit is essential for their safe transportation and storage.

An ideal fruit package ensures that the fruit is completely protected from physical damage and does not spoil. During transport and storage, jujube fruit are susceptible to infection with bacteria and fungi, especially if organic packing or cushioning material is used for packaging. A freshness-promoting paper bag, treated with Chinese herbal medicine, can also be used for packaging to reduce the incidence of rotten *Z. jujuba* fruit (Zhang, 2004).

Perforated polythene bags (150 gauge), nylon nets or cardboard cartons can be used to package small quantities of fruit of 1–2 kg. For larger volumes of fruit (10–20 kg), gunny bags, cloth packages or wooden boxes with holes or slits are used. Baskets made from locally available materials such as bamboo can also be used. For transportation, corrugated cardboard cartons holding about 5 to 10 kg are the most suitable packaging material. Shredded paper is the best material for cushioning and protection during transport (Zhang and Li, 2007). For short distances, cheaper materials such as gunny bags, cloth or old boxes can be used provided that the fruit are cushioned and ventilation is provided (Zhang and Li, 2007).

Small quantities of about 1 to 3 kg fruit for retail sale should be packaged in transparent plastic bags, plastic bags with holes, or mesh bags. These are not only beneficial for extending the fruit shelf life, but are more aesthetically appealing to customers (Zhang and Li, 2007).

13.8 Processing

Jujube can be used to prepare various processed products such as dehydrated products, candy, juice, wine, vinegar, jam, jelly, slices and powder, as well as fresh cut fruit (Wan *et al*., 2009) (see Fig. 13.1). Here we discuss only dehydrated products, candy, juice, beverages and frozen fruit, which are the most significant processed products.

13.8.1 Dehydrated jujube products

Drying fresh jujube reduces the water content from about 70% to about 25%. The increased concentration of TSS means that it is difficult for microorganisms to survive and the resulting dehydrated jujube products are consumed worldwide (Khurdiya and Roy, 1986; Chen, 1985).

Briefly, the process for production of dehydrated jujube is as follows: cultivation → timely harvesting → fruit classification and selection → cleaning → pre-treatment → oven-drying → temporary softening → packaging → storage → market. The fresh jujube fruit that are chosen should be consistent in color and size, at the ripening stage and free from pests. When the jujube drying process is complete, the fruit should be placed indoors so that it can reabsorb a certain amount of water and therefore soften before packaging (Chen, 1985).

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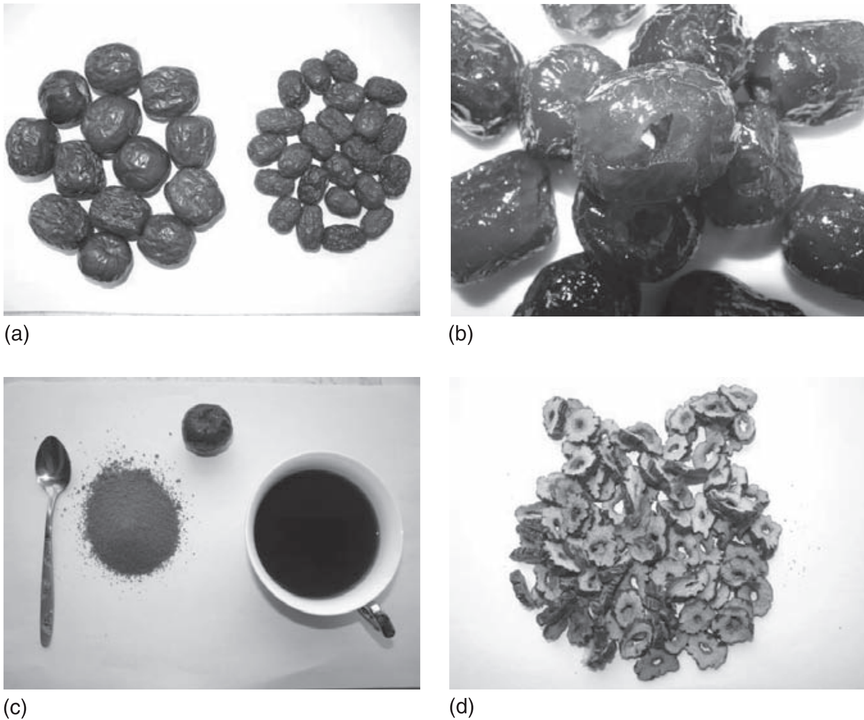

Fig. 13.1 Processed Chinese jujube: (a) dehydrated jujube; (b) candied jujube; (c) jujube powder; (d) sliced jujube.

13.8.2 Candied jujube

Candied jujube is produced by boiling the fruit in a sugar solution to increase the sugar concentration to a certain point, then drying it. The surface of the candied jujube is brown and it is a very popular product in China and India (Ma, 2003; Gupta, 1983).

The process is as follows: fruit classification and selection → cleaning → size reduction → candying → soaking → baking → packaging in plastic bag.

It is possible to use honey instead of sugar in the process. The product is then known as 'bee-sugar candy' (Ma, 2003).

13.8.3 Jujube juice and beverages

Juice and beverages can be made from either fresh jujube or dried jujube (Shi and Qi, 2002; Khurdiya, 1980).

Briefly, the processes are as follows:

- Juice from fresh fruit: selection of fresh fruit → washing → draining → baking → soaking and juice extraction by filtering → ingredient addition → preheating → bottled degassing → sterilization → cooling.

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- Juice from dried jujube: selection of dry dates → loading → cleaning → softening → draining → breakdown of jujube → extraction → first filtration → second filtration → concentration → sterilization and aseptic filling → finished product (Shi and Qi, 2002).

Juice from fresh jujube fruit is clear like apple juice. Juice from dried jujube has a distinctive dark red color and a sweet, delicious flavor. However, health drinks which are a mixture of jujube and other ingredients are more nutritionally complete and often more fit for healthy purpose.

13.8.4 Frozen jujube fruit

Freezing is also a potential method of jujube fruit storage. Wei and Deng (2002) examined frozen storage of 'Lizao' Chinese jujube, and reported that 'Lizao' frozen at −50°C retained its high quality for 8~12 months at −22°C to −35°C. Following storage for 8 months, the ascorbic acid retention was found to be 52.8 ~ 62.6%, and firmness retention 70.1~78.6%, after thawing at room temperature.

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(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(i)

(j)

Plate XXIII (Chapter 13) The different varieties of jujube: (a) Budaizao; (b) Fangyuanguiyizao; (c) Longzao; (d) Jinsixiaozao; (e) Yuanlingzao; (f) Mumzao; (g) Chahuzao; (h) Twinszao; (i) Junzao; (j) Dongzao.

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14

Kiwifruit (*Actinidia* spp.)

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Abstract: The global kiwifruit industry has been built almost exclusively on the green-fleshed *Actinidia deliciosa* cultivar 'Hayward'. It could be said that without the unusually good postharvest performance of 'Hayward', there may not have been the opportunity to create the global market for kiwifruit as it exists today. The postharvest performance of 'Hayward' fruit is largely the result of a tolerance of low temperatures used for storage. This chapter reviews kiwifruit, with a focus on fruit physiology and the way it affects the commercial postharvest sector, based largely on what is known about the 'Hayward' and 'Hort16A' cultivars.

Key words: kiwifruit, postharvest physiology, physiological disorders, commercial handling and storage, postharvest pathology.

14.1 Introduction

Kiwifruit belong to the genus *Actinidia*, which comprises a diverse range of species, the two main commercially significant species being *A. deliciosa* and *A. chinensis*. There are 55 species and about 76 taxa currently recognised within the genus (Li *et al.*, 2007), although this is being continually revised in the light of new information. Most taxa occur in south central and southwest China, an area regarded as being the centre of diversity and evolution of *Actinidia* (Liang, 1983). Most of the fruit that are currently being commercialised are the larger fruited selections of *A. deliciosa* or *A. chinensis*. An exception is the fruit of *A. arguta*, which are small grape-sized fruit that have to be handled and marketed like berryfruit.

From the initial introductions of seed into New Zealand in 1904 (Ferguson, 2004), several kiwifruit strains were developed with commercial potential, including 'Abbott', 'Allison', 'Bruno', 'Hayward' and 'Monty'. As more significant volumes of fruit began to be exported from New Zealand in the 1960s, the postharvest performance of the fruit became more important. 'Hayward' became the dominant cultivar because of its superior flavour and postharvest performance.

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Production in other countries was based on 'Hayward' sourced from New Zealand, resulting in the globally traded kiwifruit industry being based for many years almost exclusively on 'Hayward'.

While the overall volume of kiwifruit traded internationally is small compared with that of some other fruits, for some countries kiwifruit is a significant economic crop. Currently, on the basis of quantities of fruit produced, the major producing countries are China (467 000 metric tons), Italy (442 000 mt), New Zealand (370 000 mt) and Chile (173 000 mt) (data for the period 2007–10; Belrose, 2010). However, the production and export circumstances of these countries differ considerably. While China is a major producer, it is a minor exporter: about 1% of Chinese production is exported compared with more than 90% of production for New Zealand and Chile. In China a wider range of kiwifruit cultivars are grown, including 'Qinmei': this is the second most commonly grown cultivar of kiwifruit, but is only important in China.

Whilst the global kiwifruit industry was developed on the 'Hayward' cultivar, that situation is now changing with the introduction and commercialisation of new cultivars. The most successful of these thus far has been 'Hort16A', which was created by HortResearch (now The New Zealand Institute for Plant & Food Research Limited) and is traded as ZESPRI® GOLD Kiwifruit. This cultivar was the result of a cross made in 1987, and was officially launched as a commercial product in 2000. 'Hort16A' belongs to the species *A. chinensis*, producing fruit with a yellow flesh and a more complex 'tropical' flavour than 'Hayward' fruit. 'Hort16A' now comprises about a quarter of the New Zealand annual export volume of about 100 m trays. There are also other new cultivars being commercialised from a range of sources. In Italy many of the new cultivars are from crossing with 'Hayward' (Summerkiwi®, 'Katiuscia') or bud-mutations of 'Hayward' (Bo-Erica®, Earligreen®, Green Light®, Top Star®) claiming advantages, such as earliness, over the traditional 'Hayward' (Ferguson, 2009; Testolin and Ferguson, 2009). There are also new *A. chinensis* cultivars other than 'Hort16A' being commercialised, of which the best known and most widely grown is probably 'Jintao' (http//:www.kiwigold.it). Notable among new commercial cultivars is 'Hongyang' (Wang *et al.*, 2003), which has yellow flesh with a red centre, giving a natural selling point.

The range of commercially available kiwifruit cultivars may increase beyond those from *A. deliciosa, A. chinensis* and *A. arguta*, in the near future. However, in general, the postharvest performance of these newer cultivars does not match that of 'Hayward' and providing quality fruit for a long selling window may be more difficult. With each of the new cultivars comes all the postharvest challenges that have either been managed, or avoided, with 'Hayward'. The ability to manage these postharvest challenges is dependent on understanding the fruit physiology.

14.2 The *Actinidia* vine and fruit

14.2.1 Vine

In the wild, the kiwifruit is a perennial climbing vine, growing in temperate rainforests. These natural origins are likely to underpin the behaviour and

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performance of the vine and fruit when grown commercially. The natural habit of the vine is to climb over other plants; commercially, the vine is provided with pergola or T-bar support structures onto which it is trained and managed.

The kiwifruit vine builds carbohydrate reserves in both the shoots and roots to provide reserves for over-wintering and for bud-break and new growth in spring before the new season's leaves become photosynthetically functional. Bud-break is dependent on chilling, although commercially this may be manipulated by the application of bud-break enhancers such as hydrogen cyanamide, which may also help condense the period over which bud-break occurs. Saturation of the photosynthetic capacity of 'Hayward' leaves is dependent on the light conditions under which the plants are grown. Plants grown under higher light conditions adapt and saturate at higher light levels than plants grown under low light conditions (Laing, 1985). Below 300 $\mu mol/m^2.s$, the rate of photosynthesis is reduced. The photosynthetic rate of 'Hayward' increases with temperature, although the difference between the rate at 10 and 30°C is only about 20% on a leaf-area basis (Laing, 1985). On a leaf weight basis, the rate is constant at temperatures above 15°C. When comparing the effect of temperature on vegetative growth rather than photosynthesis, 'Hayward' vines have been shown to have a wide temperature optimum between 20 and 30°C (Morgan *et al.*, 1985).

Water is critical for the uptake of minerals and the movement of metabolites within the vine. Within the natural rainforest environment, water would not generally be limited: under commercial conditions water must be supplied by irrigation if natural rainfall is lacking. Adequate water supply is essential for steady fruit growth, particularly during the initial phase of fruit expansion. It has been estimated that a commercial kiwifruit vine uses about 100–150 L of water per day in the New Zealand climate (Clothier and Scotter, 1983; Sale and Lyford, 1990). Whilst water is essential for vine and fruit physiology, too much is detrimental; kiwifruit appear to be very sensitive to flooding and root anoxia (Smith *et al.*, 1990). The extent of the root system is likely to be dependent on the soil type and depth. On a forest floor or in shallow soils, the root system may be shallow. In deeper soils, such as exist around the main kiwifruit growing area of Te Puke in New Zealand, root systems have been found to extend beyond 4 m (Greaves, 1985).

14.2.2 Fruit

The commercially grown kiwifruit of *A. deliciosa* and *A. chinensis* are berries that are typically ovoid in shape, although size and shape vary among cultivars. The fruit have a brown skin and are covered in uni- or multiseriate hairs. The number and size of hairs differ among cultivars; 'Hayward' hairs are more numerous and robust than those of 'Hort16A'. By the time the fruit are harvested, these hairs are dead and easily removed. The skin comprises several layers of dead compressed cells, with no specific peel tissue such as occurs in citrus or banana fruits, and no thick waxy covering (Hallett and Sutherland, 2005). The dead skin cells are suberised and accumulate phenolics to differing degrees, dependent on exposure

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to the sun. A fruit grown in full sunlight will develop a very brown skin whereas a fruit grown under a dense canopy will have a greener appearance.

In early harvested 'Hort16A' fruit the skin layer may be scuffed easily to reveal the fruit flesh beneath. As the fruit develops further, the fruit skin becomes harder to scuff, making the fruit more durable for handling. The change in skin adhesion may be associated with the completion of the death and compression of those layers of cells that form the skin. There is a clear delineation of cells that will form the skin from those of the fruit flesh (Hallett and Sutherland, 2005). Early in development, not all the cell layers that will form the skin have died and been compressed. The lower layers of cells that will eventually form part of the skin are still living and may form a line of weakness between the already dead skin cells and the outer pericarp. Once all the skin cells have died, and been compressed, the ability to separate the skin from the fruit flesh may be reduced. This change in skin condition also appears linked to a reduction in the skin permeance of more mature fruit (Celano *et al.*, 2009).

One final, but very obvious, external feature of 'Hort16A' fruit is the presence of a pronounced protuberance or 'beak' at the distal end of the fruit. The protuberance in 'Hort16A' is the most marked of the currently commercialised cultivars, many of which have no protuberance.

Internally kiwifruit comprises an outer and inner pericarp surrounding a central core or columella. Much of the cell structure of the fruit has been described for 'Hayward' or other earlier cultivars (summarised by Beever and Hopkirk, 1990). The outer pericarp comprises both small spherical cells and also larger, elongated cells that may be up to 1 mm in length. There appears to be a fundamental difference between the small and large cells of the outer pericarp. While the small cells accumulate large numbers of starch grains during fruit growth (Hallett *et al.*, 1992), and also contain the cysteine protease actinidin (Nieuwenhuizen *et al.*, 2007), the larger cells do not accumulate starch or actinidin to the same levels. Differences between the two cell types also occur during ripening. The cell walls of the smaller cells show swelling coincident with fruit softening, whereas the cell walls of the large cells do not swell (Hallett *et al.*, 2005). In the outer pericarp, there are also cells which contain calcium oxalate crystals within a mucilage sheath (Strauss, 1970). In 'Hort16A', but not 'Hayward', stone cells are present in the outer pericarp (Hallett and Sutherland, 2005): in general, stone cells tend to be present in *A. chinensis* but absent from *A. deliciosa* (P. Sutherland, pers. comm.).

The inner pericarp comprises locules in which there are two radial rows of seeds within a mucilaginous matrix (Ferguson, 1984). Clearly visible with little magnification are numerous calcium oxalate crystals in the inner pericarp around the seeds. While oxalic acid may be present in both soluble (oxalic acid, potassium oxalate, sodium oxalate) and insoluble forms (calcium oxalate crystals), it is the insoluble crystals that receive most attention, as one form of crystal is a needle-like raphide that may cause irritation in the throat and mouth when eaten (Perera *et al.*, 1990; Walker and Prescott, 2003). The distribution of oxalate in the fruit is not uniform, being most concentrated in the skin and inner pericarp. Biologically, oxalate has tended to be regarded as a sink accumulating from excess ascorbate

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(Keates *et al.*, 2000), and kiwifruit are typically high in ascorbate or vitamin C (Ferguson and MacRae, 1991). More recently, it has been suggested that oxalate formation is not simply a dead-end, but that its formation is regulated in association with ascorbate metabolism (Rassam and Laing, 2005).

The presence of the oxalate crystals is significant when the calcium nutrition of the fruit is being considered, as a variable amount of calcium may be bound in the crystals and not be available physiologically. Hence while the total calcium content of 'Hayward' appears to be high (10–25 mg/100 g f.w.; Ferguson *et al.*, 2003; Thorp *et al.*, 2003) compared with that in fruit such as apples (Ferguson *et al.*, 1980), the bound proportion must be taken into consideration in determining whether calcium is limiting in the fruit or not. This aspect of the calcium balance of the fruit may in part account for the variable reports on whether calcium plays a role in fruit firmness retention in 'Hayward' (Hopkirk *et al.*, 1990; Gerasopoulos *et al.*, 1996).

The central core is white-ish and comprises large, homogeneous parenchyma cells. These cells also soften as the fruit ripen, although the timing of changes in the pericarp and core may differ. At the stem-end of the fruit there may be some sclerified tissue just below the picking scar that creates a hard 'woody spike', although in most fruit this is barely noticeable.

A range of ripe fruit flesh colours exists within the *Actinidia* genus. These flesh colours include green, yellow, orange, red and purple. In 'Hayward' the green flesh colour present at harvest persists, or changes little, during storage and ripening. In contrast, the newer commercial introductions have included the yellow-fleshed *A. chinensis* fruit 'Hort16A' and 'Jintao', and also the yellow/red-fleshed 'Hongyang'.

The difference between cultivars in which the fruit flesh is green or yellow when ripe is the capacity to degrade chlorophyll. Both green- and yellow-fleshed fruit contain a similar range of pigments. These pigments include chlorophylls and carotenoids, including lutein and β-carotene (Gross, 1982; Watanabe and Takahashi, 1999; McGhie and Ainge, 2002). However, this does not mean there is no change in the colour of 'Hayward', just that it is very slow and while a decrease in chlorophyll has been recorded after storage (Ben-Arie *et al.*, 1982), the loss may not be visibly noticeable. Chlorophyll loss in air storage may be more noticeable than in fruit stored in controlled atmospheres (CA) for 5–6 months, as CA retards chlorophyll loss, making for a noticeably greener flesh colour than in air-stored fruit (Lallu *et al.*, 2005). The amount of chlorophyll in fruit may also differ at harvest depending on growing conditions.

In 'Hort16A' fruit, the change in flesh colour from green to yellow occurs as the fruit mature and ripen (Patterson *et al.*, 2003). There is no increase in the carotenoids during maturation or ripening, and it is their unmasking through a reduction in chlorophyll that causes the change in colour (Montefiori *et al.*, 2009). However, degreening in 'Hort16A' is not tightly linked to other commonly measured fruit characteristics, such as soluble solids content (SSC) and firmness. Hence, depending on environmental conditions, 'Hort16A' fruit may be fully degreened, firm and with a low SSC, or may still be green yet soft and with a relatively high SSC.

The basic chemical composition of 'Hayward' kiwifruit has been described in previous reviews (Beever and Hopkirk, 1990; Given, 1993; Cheah and Irving,

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1997; Perera *et al.*, 1998). When considering these data, the following points should be considered. Firstly, much of the early work may have been undertaken on cultivars other than 'Hayward', such as 'Bruno'. Secondly, the current crop loading and orchard management practices for 'Hayward' differ markedly from those in the earlier days of research. These changes in commercial practices (crop load, pruning for open canopies, girdling and the use of biostimulants) may alter the absolute compositional values, but not the fundamental nature of the fruit. Physical data on the heat transfer characteristics of 'Hayward' fruit relevant to cooling and storage have been published (Harris and McDonald, 1975).

One fundamental aspect of kiwifruit physiology is the way in which non-structural carbohydrates are accumulated within the fruit. The products of photosynthesis are initially stored in the fruit as starch, with a relatively low rate of increase in soluble sugars. Starch may comprise up to 50% of the dry matter of the fruit. Later, the developmental state of the fruit changes from starch, accumulation to starch breakdown and starch is converted to soluble sugars, resulting in a rapid increase in the rate of soluble sugar accumulation. The soluble sugars that result are mainly hexoses rather than sucrose. While myo-inositol is commonly found in plants, the concentrations found in kiwifruit are high compared with those in other plants (Bieleski *et al.*, 1997). *A. arguta* differs from *A. deliciosa* and *A. chinensis* in that the fruit accumulate greater amounts of sucrose (Boldingh *et al.*, 2000) and the trisaccharide planteose has been recorded as a short-term storage carbohydrate in the leaves (Klages *et al.*, 1997).

Early research on kiwifruit physiology reported that ethylene production increased in the fruit towards the end of ripening (Pratt and Reid, 1974). As a consequence, kiwifruit have been categorised as climacteric fruit. However, in kiwifruit, the occurrence of a marked increase in, or even detectable amounts of, ethylene does not occur until the fruit are <1 kgf (Wright and Heatherbell, 1967; Kim *et al.*, 1999; Ritenour *et al.*, 1999). The increase in ethylene production in kiwifruit at <1 kgf was found to occur irrespective of coolstorage (Kim *et al.*, 1999; Yin *et al.*, 2009) or previous ethylene treatment (Ritenour *et al.*, 1999). Such a pattern of ethylene production is markedly different to that in climacteric fruit such as tomato, banana or avocado, in which ethylene production is more closely associated with the initiation and progress of softening. The pattern of ethylene production of 'Hayward' has led to the suggestion that it may be a form of ripening mutant (Hewett *et al.*, 1999). Higher ethylene production in other kiwifruit cultivars may be associated with lesser storage performance (Cotter *et al.*, 1991). Therefore, it is perhaps better not to regard kiwifruit strictly as climacteric or non-climacteric, but rather as a fruit that fits into a climacteric–non-climacteric continuum.

14.3 Maturation

Maturation is usually portrayed as a phase in which the fruit develops the capacity to ripen, and is the phase in the development of a fruit that occurs after the

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completion of growth and before the fruit ripens and finally senesces. Numerous biochemical changes occur in the fruit as growth concludes and ripening starts, which occurs in 'Hayward' about 160 days after fruit set. These changes may overlap to a lesser or greater degree depending on factors such as the environment, which may influence both the condition of the vine and also separately the fruit. As such, there is not a single state that may be defined as physiological maturity, rather a period over which the various aspects of growth and ripening become less or more dominant.

The most obvious changes in the fruit as it matures are the slowing and cessation of growth, and the accumulation of carbohydrates. Fruit growth is often described as either a single or multiple sigmoidal pattern. Reports on the growth pattern for kiwifruit have been inconsistent, with double (Hopping, 1976) and triple (Pratt and Reid, 1974) sigmoidal patterns reported. Beyond the basic periods of cell division and cell enlargement, periods of fast and slow growth may be associated as much with environmental conditions such as water availability, as with any genetically based growth patterns. Growth rates for both 'Hayward' and 'Hort16A' fruit have been reported as being up to 1.5 g/d, peaking at 35–50 days after flowering (Patterson *et al*. 2003). The final decline in growth rate at maturation is accompanied by an overall change in the vine, where the photosynthetic productivity of the vine declines and leaves begin to yellow before being shed.

The change from starch accumulation to breakdown occurs about 17–20 weeks after anthesis (Beever and Hopkirk, 1990), but there may be considerable variation from year to year. The timing of the change from starch accumulation to breakdown is dependent to some degree on low ambient temperatures, usually cold night temperatures (Snelgar *et al.*, 1993; Burdon *et al.*, 2007a). Precise temperatures required for starch breakdown have not been determined, although associations with air temperatures below 7 or 10°C have been published (Burdon *et al.*, 2007a). With the change to starch breakdown being dependent on the environment, it is not possible to predict the change earlier in the season with any degree of accuracy, beyond any ability to predict the weather. This explains why predicting the timing of changes in SSC accumulation from whole-season temperature data is not always successful.

Seed colour changes from white, through brown to black before the cessation of growth (Pratt and Reid, 1974). Acidity peaks about the same time as the change to starch breakdown (Beever and Hopkirk, 1990). The respiration rate of the fruit gradually declines with increased maturity, but with no marked change. Ethylene production at commercial harvest is negligible and usually not detectable, being less than 0.01 nL/kg.h.

The rate of softening of the fruit on the vine may increase around the time of maturation. The firmness at which any change in the rate of softening occurs is not fixed and may differ considerably among fruit from different orchards or among fruit from the same orchard in different seasons. This has been most noticeable in 'Hort16A' fruit, since they may be left on the vine until quite soft while waiting for flesh colour to change (Burdon and Lallu, 2009). The timing of colour change

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in 'Hort16A' is not tightly linked to firmness or SSC changes, and what controls flesh colour change is not known. The relative roles of fruit development, vine management and environmental conditions in the control of colour change have yet to be determined.

Instead of assessing the stage of fruit development on the vine on the basis of composition, it may be better to look at the development of the capacity to soften. Fruit harvested very early, very immature, may never soften fully to a firmness suitable for eating (0.6–0.8 kgf), but may soften if treated with ethylene. The response of fruit to ethylene changes with maturity (Lallu *et al.*, 1989). Given a brief low dose of ethylene, immature fruit may start to soften but not soften completely, in that they have not developed the capacity to respond fully to the initial ethylene stimulus. More mature fruit would respond to the same ethylene dose by softening fully. This contrasts with fully mature fruit that will soften fully after harvest in the absence of any exogenous supply of ethylene, and for which even low concentrations of applied ethylene will accelerate softening. Hence the softening of the fruit after harvest, and response to ethylene, discriminates stages of fruit development on the vine dependent on the inherent capacity to soften.

The physiological changes that occur in fruit at the time of maturation are complex and not fully understood. This makes the determination of suitable harvest indices difficult, since the ability to predict the storage performance of fruit on the basis of a visible, or easily measureable, aspect of the fruit is limited (see section 14.9.1).

14.4 Postharvest physiology

The postharvest physiology of kiwifruit is largely associated with the behaviour of the fruit at low temperatures used for storage. 'Hayward' fruit are stored at temperatures around 0°C, whereas 'Hort16A' fruit are stored slightly warmer at temperatures around 1°C. Kiwifruit softening during storage is important, as fruit are harvested while firm and unripe and are required to soften to an acceptable eating texture or firmness. In addition, firmness is used as the principal quality criterion for fruit being traded and determines limits for commercial handling procedures. Firmness of kiwifruit is usually measured with a penetrometer as the force required to push a 5/16th inch (7.9 mm) diameter probe a distance of 7.9 mm into the outer pericarp of the fruit after removal of the skin and flesh to a depth of about 1 mm. In addition to softening, key aspects of ripening are the development of an acceptable flavour and a lack of physiological disorders. The physiology of softening, including the role of ethylene, other aspects of ripening and the response to low temperatures are discussed in the next section.

14.4.1 Softening

The softening curve from an inedible to an edible fruit for 'Hayward' and 'Hort16A' fruit has three discrete phases: an initial slow phase followed by a rapid

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phase and finally a second slow phase once the majority of softening has occurred (Beever and Hopkirk, 1990; MacRae and Redgwell, 1992; Patterson *et al.*, 2003). The same softening pattern occurs both on the vine and also off the vine in storage. The softening curve in storage is thus dependent on the stage in softening that has been achieved at the time of harvest. In less mature fruit, the capacity to soften fully may not have developed and the initial period of slow softening may be prolonged in storage. Very immature fruit may not show a change to more rapid softening in storage. Instead, these fruit may soften slowly in a more or less linear fashion. However, whilst these fruit retain firmness well during storage, on removal to higher temperatures, the fruit may soften rapidly and show symptoms of low temperature disorder. In more mature fruit in which the initial change from slow to fast softening has occurred on the vine, only the fast and second slow phase are apparent in, or after, storage. Given the known pattern of softening, empirical modelling has been shown to describe the softening of kiwifruit in storage accurately, although such models have little predictive value (Benge *et al.*, 2000). A more mechanistic approach is needed for prediction, requiring an understanding of the biological processes occurring during softening. This knowledge may also assist in being better able to manage and manipulate the process after harvest.

Despite not producing large amounts of ethylene until soft, kiwifruit are very sensitive to ethylene and the presence of even low concentrations of 0.01–0.03 ppm ethylene in the store atmosphere can accelerate softening, even at storage temperatures (McDonald, 1990; Jeffery and Banks, 1994). Maintaining firmness during storage is therefore dependent on avoiding exposure of the fruit to ethylene by ventilating or scrubbing the store atmosphere to remove ethylene as necessary. In New Zealand, ethylene concentrations are maintained at less than 0.03 ppm within the coolstore throughout storage.

The lack of an increase in ethylene production associated with the major period of softening does not mean that ethylene is not involved. Application of the inhibitor of ethylene action 1-methylcyclopropene (1-MCP) at very low concentrations shortly after harvest slows kiwifruit softening (Crisosto and Garner, 2001; Kim *et al.*, 2001; Boquete *et al.*, 2004; Sfakiotakis and Koukounaras, 2007; Koukounaras and Sfakiotakis, 2007; Regiroli and Vriends, 2007). Whilst not having as marked an effect on softening as in apples (Watkins, 2008), the fact that 1-MCP affects softening is indicative of a role for ethylene. The ethylene involved may be a low concentration continually present in the fruit, described as System I ethylene (McMurchie *et al.*, 1972), or small amounts of ethylene produced in response to harvesting. In addition, 1-MCP prevents accelerated softening in response to exogenous ethylene. The failure of 1-MCP to have a more marked effect on slowing softening may suggest that there may be components of softening that are not ethylene regulated, or that ethylene receptor turnover is rapid.

1-MCP is registered for use through the SmartFresh^{SM} system in most of the major kiwifruit producing and exporting countries (http://www.agrofresh.com). While 1-MCP slows rather than stops softening, the effect has been shown to

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produce positive results in commercially handled fruit (Regiroli and Virends, 2007; Lallu and Burdon, 2007). Small differences in firmness in fruit whilst they are softening rapidly may make little difference to the commercial quality of the fruit, yet 1-MCP seems to reduce the numbers of fruit that soften excessively, thereby reducing the incidence of over-soft fruit in a commercial consignment. This effect may be associated with components of softening that are ethylene dependent or independent and the timing at which specific aspects of cell wall modification may occur. It has also been observed that 1-MCP maintains fruit firmer for longer during shelf-life evaluation (Burdon *et al.*, 2007b).

While the softening of 1-MCP treated fruit is slower than untreated fruit, this has not been found to affect the overall consumer acceptability of the fruit (Regiroli and Vriends, 2007; Harker *et al.*, 2008). This suggests that if there are ethylene dependent and independent components of softening, or other aspects of ripening, their dissociation by 1-MCP does not alter the ripe fruit in any detrimental way.

Changes in cell wall composition and associated enzyme activity have been studied extensively and reviewed recently by Schröder and Atkinson (2006). The process of softening is complex and thought to involve several different components of the cell wall and associated enzymes. The process has been suggested to start with pectin softening (Newman and Redgwell, 2002), solubilisation, and de-esterification, an increase in pectin methyl esterase and increased cell wall swelling (MacRae and Redgwell, 1992; Schröder and Atkinson, 2006). At the time of maximal softening rate, there is degradation of soluble pectin, loss of galactose and a decrease in the molecular weight of xyloglucan in the cell wall. Finally, as the rate of softening decreases at a firmness of about 1 kgf, there is further pectin solubilisation and maximal cell wall swelling.

Much of the initial work on cell walls used ethylene-treated fruit. Given the role that ethylene may have in controlling softening, or aspects of softening, relating specific cell wall changes to timings within the softening curve of the fruit may be confounded by the response to ethylene treatment. Assessing fruit left to soften on the vine, the fruit still showed pectin solubilisation, cell wall swelling and galactose loss, but the relative timings of changes were different from those during the softening of ethylene-treated fruit (Redgwell and Percy, 1992). Inhibition of ethylene production in discs of kiwifruit outer pericarp inhibited softening and pectin solubilisation, but did not affect galactose loss, leading to the suggestion that the two processes were not inter-related and that galactose loss was independent of ethylene production (Redgwell and Harker, 1995).

Several enzymes associated with cell wall modification have been isolated from kiwifruit, including pectin methyl esterase (PME), polygalacturonase (PG), β-galactosidase, xyloglucan endotransglucosylase/hydrolase (XTH) and mannan transglycosylase (Schröder and Atkinson, 2006). However, while these enzymes are specific to classes of cell wall compounds, their roles in the softening process and the way they interact or are controlled have not been fully elucidated.

Both PME and a PME-inhibitor protein have been isolated from ripe kiwifruit (Balestrieri *et al.*, 1990; Ciardiello *et al.*, 2004) and PME activity increased with

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ethylene treatment of firm fruit, but then declined as fruit softened (Wegrzyn and MacRae, 1992). PG activity appears to be associated with the later stages of softening, at which time pectin degradation rather than solubilisation is occurring (Bonghi *et al.*, 1996; Schröder and Atkinson, 2006). More specifically, three PG genes from kiwifruit have been characterised (Wang *et al.*, 2000). Of these genes, two were found to be expressed only during the final (Phase 3) stage of softening. The third PG gene was expressed throughout softening, but its expression increased during the later phases of softening. β-galactosidase activity was found to remain constant during the period of greatest galactose loss from cell walls, which coincided with the greatest rate of softening (Wegrzyn and MacRae, 1992; Bonghi *et al.*, 1996), although an increase in activity was found during the final phase of softening (Bonghi *et al.*, 1996).

While determining changes in fruit at different firmness helps describe what is changing, it does not address the question as to what controls the timing of ripening. The involvement of ethylene receptors in controlling the time of fruit ripening is a concept that has recently been proposed in tomato (Kevany *et al.*, 2007). This is based on initial observations in *Arabidopsis* and tomato that ethylene receptors negatively regulate ethylene responses (Hua and Meyerowitz, 1998; Tieman *et al.*, 2000). A reduction in specific members of the ethylene receptor gene family is associated with early ripening. In addition, application of ethylene to immature fruit reduces the amounts of receptor proteins and causes earlier ripening. Gene families associated with the ethylene signal transduction pathway in ripening 'Hayward' kiwifruit have recently been isolated from the Plant & Food Research kiwifruit expressed sequence tag (EST) database (Yin *et al.*, 2008). The genes included five ethylene receptor genes, two CTR1-like genes and an EIN3-like gene. The ethylene receptor *AdETR1* was found to be down-regulated by ethylene and 1-MCP prevented this ethylene response. It was proposed that *ADETR1* may have a role in ethylene sensing within the signal transduction pathway. If changes in expression levels of *AdETR1* lead to a change in ethylene receptors in the fruit, then a change in the fruit response to ethylene may occur without the requirement for an increase in endogenous ethylene production. This may explain the lack of ethylene production, yet responsiveness to ethylene and 1-MCP of kiwifruit.

The capacity to manipulate softening after harvest lies in the response of the fruit to low storage temperatures or to changes in the storage atmosphere. Usually, the aim after harvest is to slow softening to prolong storage, although for early harvested fruit for immediate marketing, ethylene may be used to ripen the fruit in a controlled manner. The principal method of prolonging storage is through the use of low temperatures to slow metabolism, both of the fruit and also of pathogens that would otherwise invade the fruit. Even small differences in temperature at about 0°C have an impact on softening (Lallu, 1997; Patterson *et al.*, 2003). Referring to the three phases of the softening curve, higher storage temperatures result in a shorter first phase, a more rapid second phase and the change from the second to third phase occurring at a lower firmness (McDonald, 1990; Patterson *et al.*, 2003).

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Modification of the storage atmosphere to prolong storage may include lowering the O_2 concentration, increasing the CO_2 concentration and removal of ethylene. Lowering the O_2 concentration suppresses metabolism generally, and specifically a lack of O_2 inhibits the conversion of ACC to ethylene (Adams and Yang, 1979). The ability to stimulate softening by propylene was retarded in a 1% O_2 atmosphere (Stavroulakis and Sfakiotakis, 1997). A lack of O_2 may induce anaerobic respiration and the production of acetaldehyde and ethanol, although the impact of anaerobic metabolism on the fruit is not clear. A short anoxic treatment, 6 h under nitrogen at an unspecified temperature, retarded softening of the *A. deliciosa* cultivar 'Xuxiang', although the production of ethanol and acetaldehyde was not quantified (Song *et al.*, 2009). Application of acetaldehyde to 'Hayward' fruit induced ethylene production and rapid flesh softening (Mencarelli *et al.*, 1991). Ethanol applications were less effective. However, in a disc system, ethanol reduced ethylene production (Massantini *et al.*, 1995). The difference between whole fruit and discs may be that the ethylene being measured in a disc system is wound induced and a greater penetration of ethanol and conversion to acetaldehyde, which is more reactive, and may reduce ethylene production (as reported in mango; Burdon *et al.*, 1996). While the risk to fruit quality from anaerobic metabolism is not clear, the risk of too low an O_2 concentration occurring during CA storage may be reduced by using dynamic CA storage to maintain atmospheres at the lowest safe O_2 concentration (Lallu and Burdon, 2007).

In kiwifruit there is a marked effect of CO_2 retarding softening in air (McDonald and Harman, 1982), or in CA or modified atmosphere (MA) storage, where it slows softening markedly beyond that achieved by low O_2 alone (Arpaia *et al.*, 1985; Harman and McDonald, 1989; Lallu *et al.*, 2003). The mechanism by which CO_2 affects firmness is not fully understood. Carbon dioxide may alter metabolism through a change in pH, thereby altering the activity of specific enzymes, especially cell wall-associated enzymes, or molecular interactions between various substrates. Alternatively, it has also been reported that CO_2 can inhibit ethylene production and activity, possibly by interfering with the conversion of ACC to ethylene, which could slow softening (Rothan and Nicolas, 1994).

Thus far, the discussion about manipulating softening has focused on slowing softening in storage. In contrast, ethylene may be used to accelerate softening, giving a method for ripening fruit in a controlled way. This is particularly useful for early season fruit harvested prior to the full development of the capacity to soften. Typically, mature fruit harvested at 7% SSC take 5–7 days to ripen at 20°C when treated with 10–100 ppm ethylene. The process of softening following ethylene treatment is dependent on the concentration of ethylene applied, the duration of the application and the temperature of the fruit when applied. The way in which the fruit ripen thereafter is dependent on the subsequent temperature management of the fruit. The correct use of ethylene can both accelerate and co-ordinate the ripening within a batch of fruit, reducing the natural variability in ripening times that exists. Incorrect use of ethylene may dissociate the textural and flavour components of the fruit or the textural components of different tissues

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within the fruit: this could result in fruit with acceptable firmness, but without acceptable flavour, or fruit with a hard core whilst the rest of the fruit is soft. The ability to ripen fruit with ethylene successfully is dependent on being able to maintain the co-ordinated process that maintains the relativity between the different aspects of ripening. Guidelines for the use of ethylene to ripen kiwifruit have been produced (Crisosto, 1997).

14.4.2 Ripening other than softening

The ripening of kiwifruit after harvest is dependent on the capacity to ripen that has developed in the fruit during maturation. While softening is a major part of ripening and eating quality, fruit must also develop an acceptable flavour, which includes aspects of both taste and aroma.

The eating quality of kiwifruit, and particularly 'Hayward', is strongly dependent on having fruit of an acceptable firmness. Research has suggested that for 'Hayward', a fruit firmness of about 0.6–0.8 kgf provides an acceptable texture for consumers (Stec *et al.*, 1989). In 'Hort16A' fruit, which are less acidic and have a more complex flavour than 'Hayward', the range of firmness at which the fruit is acceptable to consumers appears to be wider, i.e. 0.5–1.0 kgf, and in particular the fruit may be eaten when firmer than would be the case for 'Hayward' (Patterson *et al.*, 2003). In both 'Hayward' and 'Hort16A', if the fruit become over-soft, a sickly sweet aroma may develop that may be unacceptable to consumers. The relatively narrow range of firmness that is acceptable to consumers may present a challenge when attempting to make sensory comparisons among samples of fruit. Not only do the fruit from different samples need to be matched for firmness, they need to be matched within the acceptable eating range. Achieving comparable firmness for sensory evaluation on a given day is made more difficult when the firmness out of storage and the underlying softening rate of the fruit samples differ significantly, such as may occur following treatment with 1-MCP.

Soluble sugars are a key component behind consumer liking of kiwifruit, with the flavour of kiwifruit based largely on a sugar–acid balance (Crisosto and Crisosto, 2001; Boldingh *et al.*, 2008). Kiwifruit develop reserves of starch in the fruit that are only partially converted to soluble sugars at the time of commercial harvest. A consistent relationship between the dry matter at harvest and the ripe fruit SSC of 'Hayward' kiwifruit has been identified (Jordan *et al.*, 2000; Burdon *et al.*, 2004). This relationship, coupled with the capacity to segregate fruit at harvest on the basis of dry matter by near infra-red (NIR) or density grading (Osborne *et al.*, 1998; Jordan *et al.*, 2000), has made it possible to examine the relationship between ripe fruit SSC and the consumer liking of 'Hayward' kiwifruit. There is a trend for an increased consumer liking with increased SSC (Burdon *et al.*, 2004; Harker *et al.*, 2009). At low SSC, the acceptability of fruit to consumers is dependent on the acidity; a lower SSC fruit is more acceptable if the acidity is also low (Crisosto and Crisosto, 2001). In New Zealand, payments made to growers for their fruit include increasing incentives based on the degree of dry

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matter in the fruit above a dry matter threshold of 14.5% for 'Hayward' and 15% for 'Hort16A'.

While not being highly aromatic, 'Hayward' kiwifruit do produce numerous volatiles (Young *et al.*, 1983). Three volatiles (hexanal, trans-2-hexenal and ethyl butanoate) have been identified as giving the characteristic 'Hayward' kiwifruit odour (Young *et al.*, 1983, Gilbert *et al.*, 1996). Aldehydes are more prevalent in unripe fruit, giving a grassy aroma, whereas esters predominate in ripe fruit, giving a sweeter, fruity aroma (Young and Paterson, 1995; Gilbert *et al.*, 1996). The production of esters occurs once the fruit are at, or softer than, eating firmness of 0.6–0.8 kgf (Stec *et al.*, 1989; Burdon *et al.*, 2005). The key ester in 'Hayward' is ethyl butanoate, although in some fruit it may not be present until well after the fruit has softened below the eating range (Burdon *et al.*, 2005). Volatiles have been shown to decline with storage (Young and Paterson, 1985), and in particular, there is a decrease in the amounts of aldehydes produced (Burdon *et al.*, 2007b).

Ethylene regulates the expression of lipoxygenase genes associated with aroma volatile production (Zhang *et al.*, 2009). The expression of specific genes was associated with the early or later stages of ripening and with the production of aldehydes or esters. Hence the differences in fruit firmness at which ester production occurs may be dependent on the firmness at which ethylene production increases.

The volatiles in ripe 'Hort16A' kiwifruit have not been examined to the extent of those in 'Hayward' kiwifruit. 'Hort16A' volatiles are characterised by the presence of terpenes including cineole and limonene in addition to the aldehydes, esters and other volatiles commonly found in 'Hayward' (Burdon *et al.*, 2007b; Friel *et al.*, 2007).

14.4.3 Low temperature responses

A major aspect of kiwifruit postharvest physiology is the chilling sensitivity of the fruit, although this has not always been recognised (Mitchell, 1990). For postharvest operations, the use of low temperatures is the primary method by which the fruit's storage life is prolonged. 'Hayward' appears to have the greatest tolerance of low temperatures of the current cultivars, although the specific nature of this tolerance is at present not known. This genotype basis for low temperature sensitivity may be modulated further by harvesting the fruit earlier or later in development, with later harvested fruit being less sensitive. Yet whilst the postharvest performance of 'Hayward' may be exceptional in comparison with other cultivars, it is still chilling sensitive and may develop chilling injury, although this is not very common in commercial situations.

Significant aspects of the fruit postharvest performance are associated with the ambient temperature to which the fruit have been exposed to prior to harvest. These include the change in starch to soluble sugar conversion (Snelgar *et al.*, 1993; Burdon *et al.*, 2007a) and the acclimation of the fruit to withstand low temperature storage (Sfakiotakis *et al.*, 2005; Burdon *et al.*, 2007a). Hence the postharvest response of the fruit to low storage temperatures needs to be considered

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in the context of the physiological state of the fruit at the time of harvest and any previous exposure to low acclimating temperatures.

Fruit softening is dependent on an integrated process involving several enzymes, each of which has a specific role in altering a component of cell walls and thus texture. The juicy smooth texture of a ripe fruit is dependent on the co-ordinated action of all these enzymes. Given that chilling injury in kiwifruit affects textural changes, ultimately resulting in tissues that are over-soft, granular in appearance or water-soaked, the co-ordinated changes that normally occur on softening may be disrupted by low temperatures. In peach, the activity of one of these enzymes, endo-polygalacturonase, has been associated with the chilling injury that results in mealiness during, or after, cold storage (Peace *et al.*, 2006).

Commonly, low temperature susceptibility of plant tissues has been associated with changes in membrane composition and function (Murata and Nishida, 1990). Composition is measured as the proportion of individual fatty acids or the ratio of unsaturated to saturated fatty acids, whilst functionality is measured by electrolyte leakage. In kiwifruit, both electrolyte leakage and the unsaturated/saturated fatty acid ratio increased more at lower temperatures (0–5°C) than at higher temperatures (15–20°C), although there were still increases at the higher temperatures (Antunes and Sfakiotakis, 2008). The change in fatty acid ratio was largely the result of a decrease in palmitic acid (16:0) (unsaturated fatty acid) and an increase in oleic acid (18:1) (saturated fatty acid). The use of low maturity, and hence more chilling sensitive, 'Hayward' fruit in this trial may have helped to illustrate the effect of low temperatures. However, in more mature 'Hayward' fruit, increased electrolyte leakage and unsaturated to saturated fatty acid ratio occurred with later harvest and longer storage (Abdala *et al.*, 1996). In this case, the measured changes may be associated more with ripening than with low temperature sensitivity or response, since harvests started when fruit were at 12% SSC and 2.7 kgf. Hence the low temperature-response of fatty acids must be considered alongside any coincidental change in ripeness.

Undamaged mature kiwifruit do not produce measureable amounts of ethylene until they have softened to <1 kgf, irrespective of temperature. When damaged, physically, physiologically or by rots, ethylene is produced irrespective of the fruit firmness. Low temperature stress or chilling injury has been found to result in ethylene production (Hyodo and Fukasawa, 1985; Feng *et al.*, 2003). Low temperature stress and chilling injury is more prevalent in less mature fruit. Hence low temperature-induced ethylene production in kiwifruit (Antunes and Sfakiotakis, 2002) may be more associated with chilling damage rather than being a fundamental response of kiwifruit.

Specific and differential responses of ethylene receptor genes have been reported from 'Hayward' fruit held at 0°C and 20°C (Yin *et al.*, 2009). The responses at 0°C could be divided into those up-regulated (*AdERS1a, AdETR2, AdETR3, AdCTR1* and four EIN3-like genes), those suppressed (*AdERS1b* and *AdETR1*) and those for which there was no change (*AdCTR2*). On return to 20°C, the *AdERS1b* and *AdETR1* genes that had been suppressed by low temperature were up-regulated, whereas the *AdETR3* was suppressed. While there were clear

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changes in these ethylene signalling-associated genes, their expression may not equate to activity, and therefore, what role the receptors play in the control of softening or ripening is yet to be determined.

Chlorophyll fluorescence has been suggested as a method for determining chilling tolerance in fruit (reviewed by DeEll and Toivonen, 2003). In kiwifruit, while firmness and SSC changes on the vine and in storage fitted single curves, the fluorescence of the fruit differed, with larger changes (lower maximum variable fluorescence values) in the stored fruit than on the vine (Kempler *et al.*, 1992). This suggests a more rapid cellular degeneration of the fruit in storage, possibly associated with lower temperatures, despite similar firmness and SSC values.

In 'Hort16A', flesh degreening was found to be highly temperature dependent (de Silva *et al.*, 2007) and to be negligible at temperatures much below 5°C. The rate of degreening was found to increase rapidly as temperature was increased from 5 to 10°C, with degreening rates at 7.5°C and 10°C being approximately 2 × and 3 × that at 5°C, respectively (de Silva *et al.*, 2007). Hence colour change must occur before fruit are placed at storage temperatures or the fruit may not develop the desired colour. This also means that low ambient temperatures may slow colour change on the vine and fruit harvested green may not degreen in storage (Burdon and Lallu, 2009).

14.5 Physiological disorders

Physiological disorders of kiwifruit are largely associated with chilling injury. The sensitive nature of kiwifruit to low but non-freezing temperatures may result in a range of symptoms in the fruit flesh or skin.

The main low temperature damage response to be reported in 'Hayward' is low temperature breakdown (LTB; Lallu, 1997). Symptoms are first seen as a granular appearance to the outer pericarp at the distal end of the fruit. In more severe instances, a greater proportion of the fruit is affected and there may be water-soaked tissues in the outer or inner pericarp. Expression of LTB may result in fruit with a soft distal end or the whole fruit may be soft and in severe cases the flesh can be seen to be water-soaked under the skin. A range of LTB symptoms in 'Hayward' fruit are illustrated in Plate XXIV (in the colour section between pages 274 and 275).

LTB symptoms may also be seen in 'Hort16A' fruit, mainly in the less mature fruit harvested at low SSC and which still have a greenish flesh colour (Clark *et al.*, 2004; Maguire *et al.*, 2005). In 'Hort16A', but not 'Hayward', symptoms of low temperature damage may also occur as a skin discoloration at the distal end of the fruit. Underneath the dark brown discoloured skin, the fruit flesh remains firm. This symptom tends to be seen in fruit that have been harvested and stored whilst still green-fleshed.

One common factor in the expression of LTB in both 'Hayward' and 'Hort16A' fruit, and skin discoloration in 'Hort16A' fruit, is that the symptoms occur first, or

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only, at the distal end of the fruit. This suggests some form of gradient in sensitivity exists within the fruit. However, in the case of LTB, the symptoms are only seen at the distal end whilst the severity is slight. In more severe incidences of LTB, the disorder may be present throughout the fruit. The dark skin discoloration of chill-damaged 'Hort16A' fruit only occurs at the distal end of the fruit. Irregular discoloured brown areas of skin or lesions that may be seen in 'Hort16A' tend to be the result of rots growing on fruit tissues that have been disordered by low temperatures. Also in 'Hort16A', round dark patches of discoloured skin may develop as a consequence of impact damage. Often the centre of the discoloured area may be punctured, probably as a result of an impact by the 'beak' of another fruit.

The expression of chilling injury symptoms in kiwifruit may be manipulated by the temperature management or storage duration of the fruit. The incidence and severity of LTB may be reduced by delaying cooling after harvest, slower cooling and storing for only a short period (Lallu and Webb, 1997). There are several physiological responses that may account for this modulation of LTB expression. Delaying cooling allows for further progress in fruit development, a degree of water loss and for fruit to recover from the perturbation of harvest before being exposed to low temperatures. Water loss during storage has been shown to reduce LTB expression, although the effect was minor compared to the effects of storage temperature and duration (N. Lallu, unpublished data). Slow cooling may be considered to act as a period of acclimation, whereby the holding of fruit at intermediate temperatures between ambient at harvest and storage temperatures results in changes in the fruit that confer the ability to tolerate low storage temperatures. Hence fruit may be manipulated at the start of storage to affect the expression of disorder later in, or after, storage.

Irrespective of the temperature regime, if fruit are not left in storage for too long, removal to higher temperatures may permit the fruit to ripen without the expression of LTB symptoms. Hence while changes to the physiology or biochemistry of the fruit may be made at the start of storage that may affect low temperature susceptibility, the final expression of disorder may be avoided if fruit are removed sufficiently early from storage temperatures. This suggests that some irreversible change occurs in the fruit during storage after which the disorder symptoms will always be expressed.

There is a range of skin markings that may be seen on kiwifruit, although most are physical in origin and only a few are what may be described as physiological disorders. The skin marking disorder that researchers have devoted most attention to in 'Hayward' is physiological pitting (PP; Manning and Beever, 1992). The symptoms are small (2–3 mm diameter) sunken areas of the fruit surface caused by the collapse of cells just below the skin which then sinks, dries out and may discolour. The susceptibility of fruit to PP appears to be orchard-specific, maturity related and differs among seasons (N. Lallu, unpublished data). The expression of PP may be exacerbated by temperature management and CA conditions, but requires long-term storage for expression (Lallu and Webb, 1997; Lallu *et al.*, 2003). Similar symptoms have been described in the literature as freezing injury and ascribed to low storage temperatures (−1 or −1.5°C) or cooling using air at −8°C (Gorini, 1991).

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Despite much effort to identify mineral or vine factors associated with the disorder, no definitive causal link has been established (Munro, 1999; Ferguson *et al.*, 2003; Thorp *et al.*, 2003; Boyd *et al.*, 2006). However, in recent years, the occurrence of PP in New Zealand fruit has been much reduced. Fruit that historically had problems in long-term storage may be sold early in the season, eliminating the problem. Fruit susceptible to PP tended to appear to be 'weak' fruit, with greenish skin that would have come from a dense area of canopy. The current trend for more open canopies reduces the production of this type of fruit.

In 'Hort16A' fruit, physiological pitting symptoms were seen in the early years of commercialisation, with symptoms being exacerbated by low temperatures (Maguire *et al.*, 2005). At the same time, small 1–2 mm dark patches were occasionally seen around lenticels. While some of these markings eventually rotted from opportunistic infection by fungi commonly found on the fruit surface, the majority did not (M.A. Manning, pers. comm.). The discoloration is possibly a result of dehydration of the area around the lenticel. Currently PP and lenticel marks in 'Hort16A' are rarely seen. This may in part be due to a slight increase in storage temperatures being used, but also to vines and canopies being more mature, and to changes in vine management.

Water loss is largely dependent on physical environmental conditions more so than the fruit physiology, although the rate at which kiwifruit lose water tends to decrease as the fruit matures and increase as the fruit ripens. Kiwifruit lose water easily and given the prolonged periods over which the fruit may be stored there is a risk of the fruit shrivelling when they have lost about 4% or more of their initial weight. This may be more of a problem in bin-stored fruit than in packed fruit which are held in bags or poly liners within fibreboard trays. The bags and liners create a high relative humidity environment and thereby limit water loss. In bins, fruit are more exposed to the store atmosphere and minimising water loss is more dependent on having a refrigeration system that allows for operation at a high relative humidity without removing water from the store atmosphere.

There have been sporadic reports of other disorders in kiwifruit, including white flecks in the core in fruit stored under CA at a high CO_2 (Arpaia *et al.*, 1985) and of hard cores in fruit, that may have a physiological basis. Many other disorders including damage due to impact, compression and scuff are the result of poor or harsh handling conditions and are not physiologically derived. Symptoms of impact and compression damage in 'Hayward' fruit are illustrated in Plate XXV. Slight impacts may result in white lines or areas in the outer pericarp whereas more severe impacts result in water-soaked tissues. Compression may result in water-soaked tissues in the outer pericarp, with opposite sides of the fruit affected at the points of compression.

14.6 Postharvest pathology

The range of pathogens occurring on kiwifruit postharvest is similar among different growing countries and also among cultivars within a single growing

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region. In New Zealand, the main postharvest pathogens that may occur include *Botrytis, Botryosphaeria, Cryptosporiopsis, Phomopsis*, and *Cylindrocarpon*. Rot expression may occur during or after storage depending on whether or not the particular organism tolerates and grows at storage temperatures (reviewed in: Pennycook, 1985; Brook, 1990; Manning *et al.*, 2003). Rots are often described by the position at which they occur on the fruit; at the stem end, body or stylar end of the fruit, and rots at a particular position may be associated more with one particular organism than others.

The occurrence of rots in kiwifruit after harvest is a result of infection of fruit in the orchard, and hence the primary point at which to control rots is the orchard. No postharvest fungicides are applied in New Zealand, although elsewhere in the world fruit may be dipped or fogged with fungicides such as dicarboximides after harvest to control rots in the storage environment.

Stem-end rots in 'Hayward' are largely the result of infection with *Botrytis* (Manning *et al.*, 2010). The rot is first noticeable as a softening of the stem end of the fruit, which is first detected by pressing on the picking scar. With time, the rot creates a visible darkening of the fruit around the picking scar. As the rot develops further, the visible darkening extends evenly down the fruit. Under the skin, the affected tissue is water-soaked. Eventually there may be a tuft of white/grey mycelium present at the picking scar or on the skin above the lesion. This mycelium may spread to adjacent fruit, creating a 'nest' of rotting fruit through secondary infection. *Botrytis* grows at low temperatures and rots are first seen after 4–8 weeks of storage, with all infections being expressed by about 12 weeks. This means that for lines of fruit with botrytis rots, once fruit with rots have been removed after 12 weeks of storage, no further expression of rots should occur. However, the presence of the rots may result in the line of fruit being soft through the action of ethylene.

Whilst symptoms develop during storage, *Botrytis* infection occurs at the picking scar during harvesting. Control of the infection process has been achieved on the orchard through a reduction of the amount of inoculum in the canopy (Manning *et al.*, 2010). Opening the canopy and reducing the layering of the canopy reduce the incidence of *Botrytis* that can develop in the canopy by minimising the amount of necrotic leaf material present. This reduces the inoculum source for infection at harvest. A further reduction in botrytis rots is achieved by the process of curing (Lallu *et al.*, 1997; Manning *et al.*, 2010), whereby fruit are held in field bins for 48–72 h after harvest at ambient conditions under cover. This procedure reduces the incidence of botrytis rots that subsequently develop during storage and appears to be associated with a degree of water loss that occurs prior to packing and/or cooling. In general, when fruit lose 0.2–0.4% water during the 24–48 h period after harvest, the incidence of botrytis rots is reduced. Botrytis rots may also be exacerbated by pre-cooling conditions that exacerbate low temperature disorders (Lallu and Webb, 1997). This may be associated with water loss or condensation at the picking scar, or with the fact that *Botrytis* is an opportunistic invader of senescent or damaged tissues.

Stem-end rots are not seen frequently in 'Hort16A' fruit, and when present they tend to occur late in coolstorage and result from an infection of the picking scar

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largely by *Cylindrocarpon*, which causes similar symptoms to *Botrytis* (Manning *et al.*, 2003). There is water-soaked tissue around the picking scar that may extend down the fruit as the rot progresses and there may be a tuft of white mycelium growing at the picking scar.

Ripe rots develop as the fruit ripen, either immediately after harvest or after a period of coolstorage. *Botryosphaeria* is one cause of ripe rot that is present and latent at harvest, and for which symptoms tend to occur only once fruit have softened to about 1 kgf. Infection by *Botryosphaeria* causes pale brown, round/oval lesions, usually on the side of the fruit. The rotted tissue is whitish and surrounded by a thin water-soaked margin. Botryosphaeria rots occur in both 'Hayward' and 'Hort16A' fruit. They are also occasionally present in 'Hort16A' fruit coming from the orchard, although these outbreaks are sporadic and may depend on seasonal environmental conditions. As the new 'Hort16A' canopies have become more established, the incidence of ripe rots in 'Hort16A' has decreased markedly, possibly because of changes in the inoculum loads as the canopy matured. The incidence of botryosphaeria rots appears to be largely dependent on seasonal environmental conditions. However, anything that delays softening during storage will also delay the appearance of ripe rots.

Another organism that causes ripe rots in soft fruit is *Cyptosporiopsis*. Symptoms are small (3–6 mm) round orange/brown sunken lesions, under which the rotted tissue is dry and brown. The development of the lesions is slow and there may be multiple lesions on the fruit. Once developed, the surface of the skin sinks, giving rise to the commonly used name fungal pitting. *Cryptosporiopsis* appears always to be present within the fruit surface as a latent infection, but rarely expresses under normal storage conditions. However, under high CO_2 conditions that may arise in CA or MA storage, or environments where ethylene concentrations are high, expression of cryptosporiopsis rots may be high (Lallu *et al.*, 2003). This CO_2 effect is seen in both 'Hayward' and 'Hort16A' fruit and may occur in fruit that are not ripe (i.e. >1 kgf). Whether this is the result of a change in the fruit or pathogen in response to the elevated CO_2 in the storage environment is not known.

A further category of rots is termed wound rots. These are opportunistic fungi that invade damaged or weakened areas of fruit, but that would not normally be able to infect a healthy fruit. The damage or weakening may be physical, where the surface of the fruit has been broken through poor handling; physiological, as occurs when fruit develop low temperature disorders such as LTB; or when the fruit has become over-ripe. Rots that come into this category include *Botrytis, Phomopsis* sp. and *Phoma* sp. *Botrytis* has been referred to earlier as the principal cause of stem-end rots in 'Hayward'; in this circumstance the picking scar may be seen as a specific form of damage to the fruit.

After a prolonged period in storage, stains may appear on the surface of the fruit. Whilst the stain is usually the result of the growth of dark-spored fungi such as *Alternaria* or *Cladosporium* on the surface of the fruit, the initial cause of the growth is the presence of a liquid such as fruit juice on the surface of the fruit, which provides a carbon source on which the rot can grow. This liquid usually

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comes from fruit that have been damaged during the fruit handling for grading and packing. Hence, while this is a rot that grows during storage, the rot does not invade the fruit; rather it grows on the surface of the fruit, and only when there is some other contaminating substance present.

A major physiological effect of rots is the resultant ethylene that is produced as the fruit tissues are damaged. This ethylene has the capacity to soften not only the fruit that is rotting, but also adjacent fruit. This softening effect may be particularly noticeable in packed fruit. A single rotten fruit in a pack may cause all the fruit in the pack to soften more rapidly than the fruit in surrounding packs, resulting in fruit in different packs having significantly different firmness values.

14.7 Postharvest handling

Handling operations have to be able to move the fruit from the vine to the pack without damaging the fruit. Physical damage to kiwifruit may occur as a result of compression or impacts, either through fruit-to-fruit contact or when fruit make contact with the handling equipment. Impact damage usually occurs in firmer kiwifruit and typically has symptoms of a white line or lines in the outer pericarp at the point of impact, caused by a failure of starch to degrade in the damaged area as the fruit ripens after the time of impact. Later the damaged area may become water soaked. Compression damage tends to occur in softer fruit (<3.0 kgf) with symptoms of water-soaked outer pericarp tissues, usually at the opposing points on the fruit where pressure was applied.

Handling systems developed for 'Hayward' have evolved for a rapid throughput of fruit that are relatively tolerant of rough handling when handled in bulk systems. With the increase in production of cultivars other than 'Hayward', these bulk handling systems have to be made more gentle to deal with fruit that may have a more delicate skin, are softer earlier in the packing season and, in the case of 'Hort16A', have a 'beak' at the distal end of the fruit that can cause damage when it makes contact with other fruit.

The damage that occurs when there is contact between a fruit and either another fruit or equipment is dependent on both the force of the contact and the state of the fruit. The force of contact is reduced by minimising the momentum of the fruit as it moves through the handling system, by the fruit being carried on moving belts or rollers rather than being allowed to move freely. Fruit are carried in bulk on belts and rollers are used for singulation, thereby reducing the risk of damage and also having fruit isolated for size grading. The risk of damage at points at which the fruit are not being carried is reduced by minimising drop heights to less than 30 cm, slowing fruit velocity with brushes or flexible flaps and using soft materials to absorb the impact energy where fruit come into contact with the equipment. This is particularly important where the fruit are released from the grader following sizing and where the grading line may be moving rapidly.

The state of the fruit that affects its response to handling is largely the firmness. The length of time that fruit may be bulk stored in bins, or passed across a grading

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line, is dependent on fruit retaining sufficient firmness to avoid compression or impact damage, usually 2.5–3.0 kgf. However, in 'Hort16A' the nature of the skin changes during fruit development. Early harvested fruit that are firm may have a skin that lifts easily on contact. This scuffing of the skin may not be immediately noticeable, but after a couple of days the damage is more obvious.

There is a risk of damage at all stages in the handling process, from the harvesting to the final filling of the packs. Fruit are harvested by hand and are usually placed into an intermediate container such as a picking apron or picking bag worn by the picker, or into a bucket, before being placed into the field bin, which contains approximately 250–300 kg of fruit.

The picking apron is not rigid and allows considerable fruit-to-fruit contact and movement as the picker moves through the orchard, whereas a semi-rigid picking bag reduces the movement of the fruit. Irrespective of type of picking container, if the fruit are dropped or thrown into the container, there is a greater likelihood of damage than if placed gently. Likewise when the fruit are transferred from the harvest container to the field bin, and during transfer of the bin to the packhouse, rough handling is more likely to result in damage.

Once at the packhouse, 'Hayward' fruit may be cured for 2–3 days by standing the bins of fruit under cover, but open to air flow (Lallu *et al.*, 1997). This process reduces the incidence of botrytis stem-end rots that develop during storage, but only if there is 0.2–0.4% water loss from fruit during the holding period. As a beneficial side-effect, curing may also reduce the low temperature sensitivity of the fruit.

As botrytis stem end rots do not tend to occur in 'Hort16A', curing is not necessary. However, for early season fruit harvested when the skin is sensitive to handling damage, delaying grading for up to 4 days reduces the amount of scuffing that occurs during grading because of the reduced fruit turgor caused by water loss. Also, scuffing that occurred during harvesting is more easily visible and fruit affected may be removed from the grading table.

Early harvested 'Hort16A' fruit usually require degreening, so the fruit may remain in the bins during degreening for a sufficient time to reduce scuffing when graded. Holding fruit in bins for degreening also assists with temperature management, given that the fruit are harvested early in the season when the ambient temperatures are warmer and the fruit are held at temperatures of 5–10°C for degreening. Under these circumstances, temperature control of packed fruit may be more problematical. Once packed inside a polybag and enclosed in a fibreboard carton that is palletised, it is much more difficult for the cooling air to reach the fruit to remove heat.

At the coolstore, the fruit may be stored packed or stored directly in the bins. Bin-stored fruit may be pre-sized prior to storage. If stored in bins, care must be taken to pack the fruit before it becomes too soft, to minimise damage. The minimum firmness limit for grading depends on the individual system, but may be between 2.5 and 3.5 kgf. Bin-stored fruit are subject to greater risk of water loss than fruit that have been packed into a fibreboard carton fitted with a poly bag. Loss of water from fruit is driven by temperature differentials, air flow and how

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full the store is. The development of an equilibrium relative humidity in the store atmosphere is dependent on water lost from the fruit. Hence the fewer fruit, or the more rapidly that water is removed from the atmosphere by the refrigeration system, the quicker the fruit will lose water. Water loss can be reduced by having a refrigeration system with a large evaporator surface and operated with a minimal temperature differential across the coil, resulting in less water being lost as icing on the coil.

Packing the fruit entails using a fruit dump to transfer fruit from the bins onto the grader, brushing the fruit to remove the fruit hairs and orchard debris such as leaves, separating the fruit so that individual fruit may be inspected and sized by weight, before fruit are dropped off the grader to be put into packs. With the increased production of 'Hort16A' fruit, grading systems have become shorter, with fewer bends and lower drop heights to reduce physical damage. Bin dumps no longer simply spill fruit from the bin onto a moving belt; instead the fruit are delivered in a controlled way by inverting the bin using a slip-sheet tipper and allowing only a slow flow of fruit from the bin. Maintaining a flow of fruit from the bin matched to the conveyor speed reduces the amount of fruit movement. Fruit with defects have traditionally been removed manually, although there has been an increased interest in and availability of vision systems capable of identifying defective fruit for removal automatically (e.g. the InVision system from Compac: http://www.compacsort.com).

Grading lines have tended to operate with fruit sitting on cups and being tipped off for packing. The amount of fruit graded is dependent on the speed of the cups and the percentage fill. Often graders may be seen operating at high speed, but with a low cup-fill. This tends to result in fruit travelling rapidly when tipped off the grader. One of the more innovative developments in grading recently has been the Calistar grader developed by Aweta (http://www.aweta.nl), in which the fruit are held under the grader. With a relatively slow speed but high fill, and very small drops when the fruit are released, gentle handling of the fruit can be achieved.

Pack filling has traditionally been by hand when fruit are packed into single-layer trays. However, for bulk loose-filled packs, fruit are automatically counted into the packs but the packs are closed by hand. There are systems currently being developed for both automated pack filling and closing.

14.8 Commercial practice

Determining the appropriate postharvest practice for commercial operations is easiest when the physiology of the fruit is understood. This physiological understanding allows commercial practice to be established to make best use of the fruit's natural characteristics, or at least manage any weakness in a predictable way. This is illustrated in the following section where harvest index, degreening of 'Hort16A', temperature management and CA storage are described.

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14.8.1 Harvest index

The terms harvest index and physiological maturity are often used interchangeably, although they are very different concepts. A harvest index should give a predicted postharvest performance or outcome. Fruit suitable for immediate sale or for long storage at low temperatures may be harvested at very different harvest indices and may be at different physiological stages of fruit development or maturation. In general terms, kiwifruit tend to be harvested when fruit growth has slowed considerably or has been mostly completed.

Kiwifruit postharvest performance is generally assessed in terms of a period of storage, after which the fruit should soften fully, develop an appropriate flavour and not develop physiological disorders. Much of this depends on the capacity of the fruit to tolerate storage at low temperatures. Kiwifruit are harvested in a once-over operation rather than having multiple harvests from an orchard. This is largely due to the lack of external clues to the fruit developmental stage that might allow selective harvesting. As a consequence, the harvested fruit are of mixed maturity and the postharvest system has to manage the differences among the fruit, in particular the capacity to tolerate temperature management regimes.

After review of several fruit characteristics, SSC was shown to be the only factor that consistently related to fruit quality after storage (Harman, 1981). In 1980 the New Zealand kiwifruit industry adopted a minimum 6.2% SSC harvest index for 'Hayward' kiwifruit for export. It was not the 6.2% SSC value that was significant; rather it was the change in the rate of SSC accumulation from slow to fast that was seen to have occurred around the time fruit reached 6.2% SSC. The change in the rate of SSC accumulation is indicative of the change from starch accumulation to starch breakdown: this is generally associated with the exposure of the fruit to some degree of cold temperature acclimation. The success of 6.2% SSC as a harvest index for New Zealand-grown fruit has resulted in 6.2% SSC being adopted elsewhere (OECD, 1992). However, there is no guarantee that under different environmental conditions 6.2% SSC has the same significance as was found in New Zealand. Likewise, fruit characteristics found not to be useful in New Zealand may still have some value under different growing conditions.

There is no reason why fruit may not be harvested earlier (Lallu *et al.*, 1989) or later than 6.2% SSC, to meet specific marketing needs. The index is only a minimum threshold, and in New Zealand, much of the 'Hayward' fruit for storage is harvested at SSC of 7–9%. Early harvested fruit present different postharvest challenges, key of which are the capacity to ripen fully and the tolerance of low temperatures, both of which may have not developed fully on the vine by the time of harvest. These limitations may be overcome by gentle temperature management, i.e. slower cooling and storing at higher temperatures, not storing the fruit for too long, and ripening the fruit using ethylene. At earlier harvest dates, fruit characteristics other than SSC may be used to indicate the state of development of the fruit. These include the development of full seed colour, which occurs well in advance of 6.2% SSC. For early harvested fruit, the flavour also has to be considered. Flavour is largely dependent on the SSC of the ripe fruit, which in turn is dependent on the amount of starch in the fruit at harvest. Early harvested

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fruit tend still to be growing and accumulating starch, which may leave the fruit low in SSC when ripe.

While the use of SSC may suffice as a harvest index for green-fleshed cultivars, for yellow-fleshed cultivars the commercial requirement is for the fruit to have degreened fully. Flesh colour is the criterion used as a harvest index for 'Hort16A'. However, flesh colour is not tightly linked to other characteristics such as SSC or firmness and may change at very different times of the season. Hence the postharvest performance of the fruit harvested at a fixed flesh colour can be variable. Fruit that have degreened early in the season may still be at a relatively low SSC (7–8% SSC) and be firm (6–7 kgf), still be growing, and not have experienced any low temperature acclimation. The overall result is that the fruit may still be sensitive to low temperatures when placed into storage, despite having the desired flesh colour. Being chilling-susceptible, these early fruit are usually marketed with minimal storage, before significant chilling injury has occurred.

As with 'Hayward', 'Hort16A' fruit may be harvested at different stages of development, provided that the knowledge as to how to handle the fruit exists. Instead of waiting for full degreening to occur on-vine, which for some orchards risks the fruit becoming excessively soft on the vine, fruit may be harvested once the flesh colour change is known to have been initiated (Burdon and Lallu, 2009). Degreening can be completed off the vine by holding the fruit at temperatures between 5 and 10°C.

To summarise, currently harvest indices are limited to simple fruit compositional measurements, as precise indices are not available to predict the capacity to ripen or tolerance to low temperatures. It is known that environmental conditions immediately prior to harvest affect the fruit's postharvest performance, but environmental data are not yet used within an index. For existing cultivars, harvest indices may differ with growing regions and, for new cultivars, new harvest indices may be required.

14.8.2 Degreening

With the commercialisation of non-green-fleshed cultivars, the issue of the fruit flesh colour, both at harvest and at the time of consumption, is important. Experience with 'Hort16A' has shown that it is not always practical to wait for full colour development to occur on the vine. Not only are there environmental circumstances that may prevent this from happening, but there are also logistical issues that limit how much fruit may be harvested or handled by the postharvest sector at one time.

Harvesting of 'Hort16A' before full colour development is possible, as degreening will occur off the vine and the capacity for fruit to soften and ripen develops comparatively early in this cultivar and is not dependent on flesh colour. However, harvesting fruit early does mean that these fruit may be sensitive to low temperatures and risk the development of chilling injury. Hence it is possible to harvest the fruit once they have started to degreen, and to complete the process under controlled temperature conditions off the vine. This provides a solution to

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some of the logistical constraints and also where the fruit are likely to soften ahead of degreening on the vine (Burdon and Lallu, 2009).

The rate of degreening is minimal at temperatures below 5°C, so degreening tends to be undertaken at temperatures between 5 and 10°C, which may also act as a conditioning period for reducing the low temperature sensitivity of the fruit. The success of degreening off the vine is dependent on the relative rates of degreening and softening. The rate of degreening is affected more by temperature than is softening, resulting in a more rapid degreening relative to the degree of firmness lost (Burdon and Lallu, 2009). Firmness is best maintained when fruit are harvested before the change in softening rate from slow to fast. Under these circumstances the fruit show a period of little or no softening during the first few days of degreening, whilst at the same time the fruit are changing colour relatively rapidly.

14.8.3 Temperature management

Removal of field heat is managed differently depending on whether bins of fruit or pallets of packed fruit are to be stored. Bins of fruit are placed directly into the coolstore following a period of curing or directly from harvest: at this stage, fruit temperatures are typically between 14 and 18°C. The desired half-time for cooling is approximately 1 day, i.e. after 5 days fruit temperature should be less than 2°C, and the time taken to reach the storage temperature should be another 5–7 days. Bins are usually stacked as a block in the room with the air passing through the bin runners and over the fruit. To achieve a half time of 1 day, air needs to be passed through the bin stack at a rate of 0.4 to 0.6 m/sec during the cooling phase. Once cooled, the air flow is reduced to 0.2 to 0.4 m/sec to reduce water loss and hence shrivel during storage.

For fruit packed after harvest and stored palletised, forced air cooling or precooling is used where there is insufficient cooling capacity in the storage rooms and/or the type of packaging is a constraint to uniform cooling within the pallet or pack and/or the half cooling time is too long. During packing, polyliners are inserted into packs to reduce dehydration during storage, but these slow the rate of cooling, despite the presence of ventilation slots in the packaging. This can be further compounded by the type of packaging used and the subsequent stacking pattern on the pallet. Single layer trays cool the fastest, since the air passes over every single layer of fruit in the pallet. In contrast, palletised bulk packs, where fruit are loose filled to give 4–6 layers of fruit in each pack, cool the slowest. Furthermore, on a Euro pallet with 10 columns of bulk packs, there are two columns of packs that are completely internal to the pallet, i.e. these columns have packs that are not exposed to the outside of the pallet. Whilst the ventilation slots in the packs allow some alignment for air to pass directly through the pallet, the desired half-time cooling rate is achieved only under forced air cooling, i.e. on a pre-cooler, or in rooms that have a high air flow or air change through the evaporators, such as 70–90 changes per hour. Typically, with forced air cooling, the half cooling time for fruit in bulk packs is 6–8 hours. In contrast,

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the half cooling times for the same pallets with room cooling is approximately 24–36 hours.

Pre-cooling is generally not used when fruit are packed after bin or CA storage. Usually there is a 4 to 10°C rise in fruit temperatures above the storage temperatures during packing, and this heat load can be removed in most cool rooms.

Following the removal of field heat, fruit temperatures may be gradually reduced to the final storage temperatures because of the sensitivity of kiwifruit to low temperature injury. For 'Hayward' fruit temperatures may be kept just above 0°C (e.g., +0.5 to 0°C) until after the SSC has increased above 10–12%, whereupon the fruit temperature is reduced to below zero (−0.5 to 0°C).

14.8.4 Controlled atmosphere storage

Controlled atmosphere storage is used to manage the harvest and to ensure an orderly supply of fruit over a wide marketing window. The ability to harvest and pack fruit at the optimum maturity can be limited by the packing capacity available but this is overcome by using CA storage, since fruit can be harvested at the optimum time and packed later.

The atmospheres commonly used for 'Hayward' are 2% O_2 with 5% CO_2 (McDonald and Harman, 1982), and for 'Hort16A' 2% O_2 and 2% CO_2 (Lallu *et al.*, 2003). The difference in CO_2 between the cultivars is because of the greater susceptibility to cryptosporiopsis rots when 'Hort16A' fruit are exposed to high CO_2 (Patterson *et al.*, 2003). With both cultivars, catalytic ethylene scrubbers are used to keep ethylene below 0.03 ppm throughout the storage period. The rate of establishment of the O_2 and/or the CO_2 in the CA after harvest is important, as a reduction in firmness retention occurs when CA establishment is delayed (Arpaia *et al.*, 1984). However, rapid establishment of the CO_2 in the CA may be associated with increased rot and disorder incidence at the end of, or after, CA storage (Lallu *et al.*, 2003). Shock treatments with high concentrations (10 to 20%) of CO_2 also reduce the rate of softening (Rothan and Nicolas, 1994) but such treatments are not common commercial practice.

Disorders seen with CA storage of kiwifruit include stem-end rots, body rots, physiological pitting and shrivel. To manage stem-end rots, the use of lower concentrations of CO_2 (Brigati *et al.*, 1989) or delayed CA establishment (Tonini *et al.*, 1999) has been suggested. Delayed and/or a slow rate of CO_2 establishment has also been suggested to reduce the incidence of physiological pitting and fungal pitting in CA-stored 'Hayward' fruit (Lallu *et al.*, 2003). Shrivel arises from water loss, which has also been implicated in physiological pitting expression (Lallu *et al.*, 2003). The relative humidity in most CA rooms used for kiwifruit is 90–94% and after 4 months of storage, water loss from fruit is about 3–4%. A disorder termed white core inclusions can occur at storage temperatures under CA with 5% CO_2, especially when ethylene is present (Arpaia *et al.*, 1985; Arpaia *et al.*, 1986).

Dynamic CA storage has been used in New Zealand but is not in common use. Similarly, whilst SmartFresh^{SM} treatment appears to be suitable as an alternative

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to CA storage for kiwifruit (Regiroli and Vriends, 2007), at present it is not used for Class I New Zealand kiwifruit.

14.9 Future trends

Future postharvest activity for kiwifruit will offer a number of challenges. There will probably be an increased range of cultivars available commercially, for which the postharvest performance is likely to differ substantially from that of 'Hayward'. Hence new approaches will have to be taken to maximise postharvest performance, particularly with respect to managing temperature sensitivity and harvesting fruit to meet specific market niches. In the laboratory, postharvest science will have to move from being descriptive of the state of the fruit, and attempting to match this to postharvest performance, to determining those factors controlling postharvest performance. To some extent this is happening through current gene expression work, and will be best achieved when aligned with other science disciplines. In the packhouse, increased automation will reduce the dependence on a labour supply that is increasingly becoming less available, or less willing, to fill some packhouse positions.

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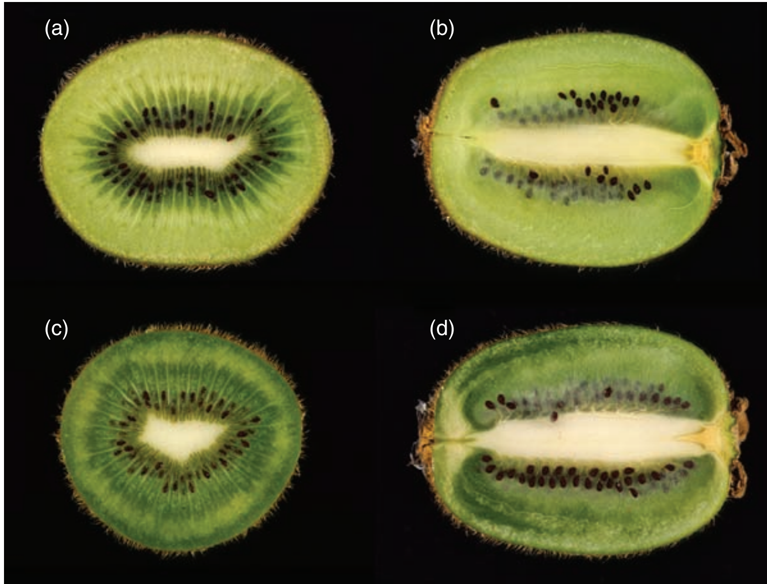

Plate XXIV (Chapter 14) Low temperature breakdown in 'Hayward' kiwifruit. (a) A continuous ring of tissue of granular appearance is present under the skin in the outer pericarp. Granular flecks deeper in the pericarp possibly indicate more extensive disordering with time. (b) A 1–2 mm wide zone of granular flecks just under the skin in the outer pericarp. The disordered tissue extends from the distal end of the fruit where it is most extensive and light brown in colour, towards the stem-end of the fruit where the flecks are sparse. (c) Water-soaked tissue in the inner pericarp and where the inner pericarp meets the outer pericarp, and water-soaked tissue with some granular tissue under the skin. A zone or ring of granular tissue is present in the outer pericarp. (d) Translucent or water-soaked tissue in the inner pericarp at the distal end of the fruit. A zone of translucent or water-soaked tissue forms a ring in the mid-region of the outer pericarp that is most extensive at the distal end of the fruit and reduces towards the equator. Granular flecks are also present throughout the outer pericarp.

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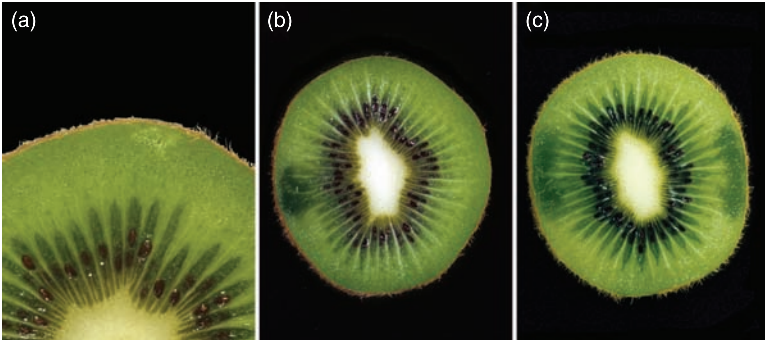

Plate XXV (Chapter 14) Impact (a and b) and compression (c) damage in ‘Hayward’ kiwifruit.

Plate XXVI (Chapter 15) Litchi fruit (cv. McLean’s Red).

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15

Litchi (*Litchi chinensis* Sonn.)

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Abstract: The litchi (*Litchi chinensis* Sonn.) is a popular export commodity due to its attractive skin colour and exotic flavour. Pericarp browning and decay are identified as major constraints affecting the quality of litchi during storage and transportation. Pericarp browning and decay are currently controlled by adopting sulphur dioxide fumigation (SO_2) and there were growing concerns regarding SO_2 residue levels present in the fruit. This chapter summarises the current knowledge on postharvest physiology, decay incidence and control, best postharvest management practices in the supply chain, and the developments in alternative treatments to replace SO_2 fumigation for maintenance of overall fruit quality.

Key words: *Litchi chinensis*, postharvest management chain, fruit quality, SO_2 fumigation, alternative treatments.

15.1 Introduction

15.1.1 Origin, botany, morphology and structure

The litchi (*Litchi chinensis* Sonn.) is a member of the family Sapindaceae, or soap berries, which includes longan, rambutan and mangosteen. It is a tropical to subtropical fruit that originated in southern China and northern Vietnam (Menzel, 2001). The litchi tree grows to 10–12 m or even 20 m and it is an evergreen tree (Zhang, 1997). It has a round, dense, compact and symmetrical crown. The branches can be curved or twisted and sometimes hang down to the ground (Subhadrabandhu and Raphael, 2005). The fruit hang from the outside of the tree. The leaves are pinnately compound with four to seven leaflets about 7 cm long. The inflorescence is determinate and composed of several panicles.

Panicles are generally 10–40 cm long and produce many small, white, green or yellow flowers. The flowers are 3–6 cm wide when they are fully opened and rest

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on 1.5 mm pedicles. The flowers have a cup-shaped calyx with short serrated sepals, and have no petals. Each flower has six to ten stamens (Subhadrabandhu and Raphael, 2005). Three types of flowers are produced by the litchi tree, namely (Stern and Gazit, 1998) functional male flowers, which lack ovules and have six to eight stamens to produce much pollen; hermaphrodite flowers, that function as female with a well developed pistil and stigma and five to eight stamens; and second type male flowers that have a rudimentary pistil lacking style and stigma (Stern and Gazit, 1996). These flowers have six to eight stamens that produce much viable pollen. The ratio of male to female flowers varies with cultivar and environment. Floral anthesis takes place in overlapping cycles, generally of 10 days for male flowers, and 7 to 10 days for hermaphrodite and for second type male flowers. The length of the anthesis cycle varies with the type of cultivar and weather and it is reported to be much shorter under warm temperatures (Stern and Gazit, 2003).

The litchi fruit is formed in a panicle and the shape of the fruit varies from conical to spherical. Fruit are green when immature. The mature fruit has a rough indehiscent red pericarp (skin) due to the presence of anthocyanins surrounding the succulent, edible aril and a seed in the centre (see Plate XXVI in the colour section between pages 274 and 275). In terms of the consumer's view, litchi fruit typically has a pinkish to bright red peel depending on the type of cultivar, a sweet and sour blend of flavour and juicy, soft and crisp aril (Nakasone and Paull, 1998). The fruit are high in sugar ad contain several vitamins and minerals. The pericarp has protuberances which are used to identify different cultivars since the protuberance type, texture and its arrangement are more reliable than fruit shape and size.

15.1.2 Worldwide importance

Litchi is grown as a commercial crop in China, South Africa, Israel, Madagascar, Mauritius, Reunion, the United States (Hawaii and Florida), Australia, subtropical parts of India, Pakistan, the Philippines, Thailand, Taiwan, Indonesia, Vietnam and Brazil (Menzel, 2001). China is the leading litchi producing country in the world with 950 000 tons of production of 40 export cultivars in 2002 (Lemmer, 2002). China and Taiwan export approximately 12 000–15 000 tons of litchi to the major international markets, Hong Kong and Singapore (Mitra, 2006). Thai litchi exports in 2007 were about 10 371 806 tons of fresh fruit and 979 717 tons of dried fruit (Office of Agricultural Economics, 2008). The European markets import approximately 20 000 tons of litchi, of which France imports around 50%, and the rest is mainly imported by Germany and the United Kingdom. The main litchi suppliers for Europe over Christmas and New Year are Madagascar and South Africa (Mitra, 2006). Fruit growers must produce high-grade quality fruits in terms of taste, colour, flavour and texture to satisfy consumer demands. Litchis are usually eaten fresh, but can also be frozen, canned, dried or processed into juice, wine, pickles, ice-creams and yoghurt.

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Pericarp browning (Huang and Scott 1985; Underhill, 1992), desiccation (Underhill and Simons 1993), postharvest decay (Swarts and Anderson, 1980) and micro-cracking (Li *et al.*, 2001) were identified as major constraints that restrict the expansion of the industry in litchi exporting countries. The litchi industry commercially uses sulphur dioxide (SO_2) fumigation to overcome these problems (Swarts, 1985). In Israel and South Africa, SO_2 fumigated fruit were subjected to dipping in diluted HCl to restore the red colour following SO_2 bleaching, a practice that has gained commercial acceptance (Zauberman *et al.*, 1990, 1991). In recent years there have been growing concerns regarding SO_2 residue levels present in the fruit, especially by importing countries such as Europe, the US and Japan. At present, the strict standards enforced on fruit imports by the European Union permit a maximum concentration of sulphur residue levels of only 10 $\mu g\ g^{-1}$ in the edible portion of the fruit (Ducamp-Collin, 2004). Therefore, this chapter focuses on current knowledge of postharvest physiology, decay incidence and control, best postharvest management practices in the supply chain and the developments in alternative treatments to replace SO_2 fumigation for maintenance of overall fruit quality

15.2 Fruit development, maturation and composition

15.2.1 Fruit growth, development, maturation and respiration

Litchi fruit takes generally 80–112 days to mature depending on the cultivar and the weather (Menzel, 2001). The colour of the pericarp changes during maturity from green to reddish pink with decreasing chlorophyll content and increasing anthocyanin synthesis (Underhill and Critchley, 1992). Litchi fruit is non-climacteric with relatively low levels of ethylene production after harvest. The fruit does not ripen after harvest and ethylene production remains constant at 1–3°C storage temperatures for 30 days (Chen *et al.*, 1968). According to Jiang *et al.* (1986), a decline in the rate of respiration was observed during fruit development. In cv. ‘Huaizhi’, the respiration decreased directly after harvest, and thereafter an increase was observed. However, there is a scarcity of information available on the rate of respiration in other cultivars.

The aril growth begins 25 days after anthesis. The aril grows continuously from about 4 weeks after flowering. The fruit normally contain one chestnut brown to dark brown, ovoid to oblong seed, 1.0–3.3 cm long and 0.6–1.2 cm wide (Subhadrabandhu and Raphael, 2005). Most cultivars have medium to large seeds, but small or shriveled seeds are observed. Fruit are drupes and can be round, ovoid or heart shaped. Fruit size can vary from 23 g to 30 g. The ratio of the edible aril to seed is more important than large fruit size. Generally the litchi fruit is approximately 5 cm long and 4 cm wide depending on the cultivar. The shapes of the cultivars are very distinctive, e.g. the round fruit of ‘Kwai May Pink’ can be differentiated from the egg-shaped ‘Tai So’ or heart-shaped ‘Haak Yip’. The fruit shoulders can be smooth or flat (‘Wai Chee’ and ‘Kwai May Pink’), or uneven (‘Souey Tung’ and ‘Bengal’). The apex or tip of the fruit does not ripen after harvest.

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15.2.2 Maturity indices and quality components

15.2.3 Chemical index for litchi maturity

The aril soluble solid concentration (SSC) is an estimate of fruit sugar content and eating quality. The litchi is a non-climacteric fruit and does not continue to ripen and accumulate sugars after harvest. Therefore, during fruit development and ripening, the SSC increases while the titratable acidity (TA) and organic acids show a remarkable decrease (Joubert, 1986; Paull *et al.*, 1984). The fruit pH increases during fruit development and ripening (Paull *et al.*, 1984). The aril SSC/TA ratio is traditionally used with pericarp colour as harvesting indices at commercial maturity. It has been proven that the SSC/TA ratio and TA are good indicators of flavour (Battern, 1989). The SSC/TA ratio is a reliable indicator for most litchi cultivars. Australia applies an SSC/TA ratio standard of 30:1 or 40:1 as determinant of harvest maturity (Underhill and Wong, 1990). In South Africa the cv. 'Mauritius' is ready for marketing when the SSC/TA ratio reaches 10:1 (Swarts, 1985). It is logical that these criteria vary depending on the cultivar and country as well as the climate of the area in which it is grown (Sauco and Menini, 1989). In Israel the SSC/TA ratio is 20:1 at maturity, and over 29:1 indicates that the fruit becomes over-ripe (Kadman and Kazit, 1970).

The content of acetaldehyde and ethanol in the litchi fruit juice on the day of harvest has been reported to increase during the season. During the second week according to the harvesting schedule, the acetaldehyde content showed an increase regardless of the pericarp colour. The acetaldehyde was at maximum level in the third and fourth weeks. Litchi cv. 'Mauritius' with red pericarp showed an SSC of 17–18% during the first three weeks of harvest. According to Pesis *et al.* (2002), the SSC level declined to approximately 14% at the fourth week of harvest. The decline in SSC with delayed harvest also increased the acidity and ethanol content during over-ripening on the tree. This suggestion was supported by the decline in O_2 uptake of the litchi aril during late maturation (Prasad and Jha, 1978). Pesis *et al.* (2002) explained that the increase in anaerobic respiration in over-mature fruit could be due to reduced mitochondrial activity and that cells were unable to produce sufficient energy. Therefore, anaerobic respiration takes place in the cytoplasm and does not require a membrane-bound organelle. Although the traditional criteria for litchi harvesting are based on colour and SSC/TA ratio, these harvest indices are not sufficient to indicate the storage potential of the fruit. The volatiles acetaldehyde and ethanol released from the fruit may be considered as predictors of over-ripeness.

The SSC/TA was observed to increase during long term storage for 21 days at 2°C and at 90% relative humidity (RH). However, the increasing effect was higher in 'Mauritius' than in 'McLean's Red' (De Reuck *et al.*, 2009). Slightly higher SSC/TA was observed in 'Mauritius' than in 'McLean's Red' at harvest (Sivakumar *et al.*, 2008b).

15.2.4 Colour and phenolic components in the pericarp

A combination of chlorophyll, carotenoids, flavones and anthocyanins is responsible for the colour of the litchi pericarp. Chloroplasts are found in the outer mesocarp mainly between the protuberances (Underhill and Critchley, 1994).

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Anthocyanins responsible for the red colour are found in the outer mesocarp and exocarp (Lee and Wicker, 1991). Cyanidin-3-rutinoside, malvidin-3-acetylglucoside and cyanidin-3-glucoside are the three anthocyanins identified in the pericarp of cv. 'Brewster' (Lee and Wicker, 1991). However, Zhang *et al.* (2000) reported that the major anthocyanin in cv. 'Huaizhi' was malvidin-3-glucoside. This discrepancy could be due to the different extraction methods used in the study. The red pigmentation occurs in conjunction with the degradation of chlorophyll and carotenoids. In some cultivars e.g. 'Feizixiao', poor colour development has been observed when the fruit are mature and harvestable due to pericarp pigmentation lagging behind sugar accumulation in the aril. If harvest is delayed, 'Feizixiao' turns fully red and less sweet due to degradation of sugars.

Changes in colour parameters during storage were cultivar dependent. The freshly harvested cv. 'McLean's Red' from this experiment lot showed higher L*, a* and b* values than cv. 'Mauritius' ('Mauritius': L* 38.2–40.12, a* 28.42, b*26.3–27.6; 'McLean's Red': L* 41.23–42.3, a* 33.89, b* 27.5–28.24) (De Reuck *et al.*, 2009). The L* value decreased with time of storage in both cultivar types (unpublished data). The Hunter colour coordinates, a* and b* were observed to decline in both cultivars during long-term storage (21 days). The colour value a* directly relates to the red colour of the pericarp and b* expresses the colour variation due to pericarp browning (lower b* indicates higher browning). The anthocyanin content was observed to reduce during storage for cvs. 'Mauritius' and 'McLean's Red' (De Reuck *et al.*, 2009). However, 'McLean's Red' showed higher anthocyanin content after 14 and 21 days' storage than 'Mauritius'. The observed difference in anthocyanin content between the cultivars was seen at freshly harvested stage ('Mauritius' 1.85–2.25 $\Delta A/g\ FW^{-1}$, 'McLean's Red' 3.12–4.5 $\Delta A/g\ FW^{-1}$). Although both cultivars were grown under similar conditions in the same orchard, the difference in anthocyanin concentration could be due to the genetic makeup involved in controlling anthocyanin levels (Matthew *et al.*, 2005). The anthocyanin content declined with increasing BI in both cultivars. This decline was higher in 'Mauritius' after 14 and 21 days and in 'McLean's Red' after 21 days.

The aril (1.4 mg $100\,g^{-1}$) has a higher phenolic concentration compared to the pericarp (0.5 mg $100\,g^{-1}$) and varies with the types of cultivars (Jaiswal *et al.*, 1986). Several phenols were identified in the litchi pericarp. 'Kwai Mi' showed flavonols, quercetin 3-rutinoside and quercetin glucoside. These compounds are ortho-diphenols and good substrates for the browning reaction. Epicatechin (1.72 mg g^{-1}), procyanidin A2 (0.68 mg g^{-1}), trimers of procyanidins (0.40 mg g^{-1}) and condensed tannins (4.02 mg g^{-1}) accounted for 90% of the phenols in 'Kwai Mi'. According to Sarni-Manchado *et al.* (2000) these flavonols are the basis of the browning reaction.

15.2.5 Fruit composition

Sugars and acids

The total sugar content increases with fruit maturity. The sugar content was reported to vary between different cultivar types (Wang *et al.*, 2006) Sucrose,

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fructose and glucose were reported as major sugar components in litchi (Paull *et al.*, 1984; Chan *et al.*, 1975; Jiang *et al.*, 2006). According to the review of Jiang *et al.* (2006) and Cavaletto (1980), the total sugars in the aril tissues vary from 55.9–61.4% on dry weight basis with 41.5–43.5% reducing sugars. The reducing sugars represent more than 70% of the total sugars in the edible portion (aril) (Jiang *et al.*, 2006). The relative ratios between these sugars depend on cultivar, stage of maturity and invertase activity (Paull *et al.*, 1984). At full maturation the sugar concentration declines as a result of increased water influx into the aril and a reduction in acid concentration, giving some cultivars a bland taste (Huang and Qiu 1987). The soluble sugars, invertase activity and colour increased simultaneously, indicating that sugar metabolism is associated with anthocyanin synthesis. Wang *et al.* (2006) classified litchi cultivars according to sugar composition into: (1) monosaccharide prevalent types, (2) disaccharide prevalent types and (3) intermediate types. This difference in sugar composition between cultivars was ascribed to differences in the activity of certain key enzymes (Wang *et al.*, 2006).

Paull *et al.* (1984) found that succinic acid is the main organic acid present during the greater part of the fruit development, whereas malic acid dominates at maturity. In contrast, Wang *et al.* (2006) found malic acid but not succinic acid. In their studies, malic acid was the main organic acid, which increased during early aril development and decreased dramatically as the fruit approached maturity. However, at harvest maturity, malic acid accounted for 80% of the acids in the fruit (Wang *et al.*, 2006). Citric, succinic, levulinic, glutaric, malonic and lactic acids were reported as relatively minor acid components (Paull *et al.*, 1984; Cavaletto, 1980; Mathew and Pushpa 1964). Citric acid was found to be low during fruit development with a slight increase towards full maturity (Paull *et al.*, 1984). Aril phenols decreased during the initial slow growth phase and remained low until full maturity (Paull *et al.*, 1984).

Ascorbic acid and mineral content

Litchi is a good source of vitamin C (ascorbic acid). The average vitamin C content in litchi is 27.6 mg 100 g^{-1}. The early maturing Hawaiian litchi cv. ‘Kaimana’ showed an average vitamin C content of 33.2 mg 100 g^{-1} and the later maturing cultivars ‘Groff’ and ‘Bosworth-3’ showed 21.2 and 22.5 mg 100 g^{-1} respectively. The vitamin C contents in ‘Mauritius’ and ‘McLean’s Red’ were 27.43 mg 100 g^{-1} and 21.35 mg 100 g^{-1} respectively. According to the reports of the Institute of Medicine (IOM, 2000) the dietary reference intake (DRI) values for vitamin C are 90 mg daily for adult males and 75 mg for adult females. Therefore, depending on cultivar, consumption of 14–17 litchi fruit would meet the average adult DRI for vitamin C (Wall, 2006). According to Gaur and Bajpai (1978) ascorbic acid increases with total sugar, but declines slightly in mature fruit when sugar accumulation slows down.

In contrast, studies by Wang *et al.* (2006) revealed that ascorbic acid decreases with fruit development until two weeks before harvest, but then increases again slightly at full maturity. Also, the vitamin C content can vary with the type of

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cultivar due to microclimatic conditions such as warm days and cool nights. The longer day lengths and higher light intensities in summer months were reported to increase the concentration of glucose (the precursor to ascorbic acid), and temperature also influences the accumulation of ascorbic acid content (Lee and Kader, 2000; Shewfelt, 1990). The cooler temperature conditions favour higher vitamin C content in litchi (Lemmer, 2000; Nagy and Wardowski, 1988).

Litchi fruit is a good source of K and N. The mineral contents such as N, P, K, Ca, Mg, Na and Fe differed significantly between the South African cultivars 'Mauritius' and 'McLean's Red', even though the two cultivars were grown under similar conditions in the same location. This could be attributed to the different patterns of mineral absorption and distribution in metabolically active tissues (Shewfelt, 1990), which could be cultivar dependent. According to Wall (2006), consumption of litchi fruit (100 g) would meet 2–4% of DRI for six minerals P, K, Mg, Fe, Zn, and Mn. It also provides 22% of the DRI for Cu. Mineral uptake into the aril takes place parallel with fruit growth and the uptake of K is higher than that of P, Ca and Mg (Paull, 1984). During fruit development K is translocated along with sugars and uptake ceases when full fruit size is attained. The Ca and Mg continue to move into the fruit after full size has been reached. However, the concentration of these elements decreases in the tissue due to the dilution effect. The uptake of Ca into the pericarp continues throughout fruit growth, unless under drought conditions (Paull, 1984; Huang, 2005).

Aroma volatiles

Volatile compounds of litchis from Florida (unspecified cultivar) were reported as having citrus flavour qualities due to the presence of limonene, geranial and neral and its floral note was mainly due to 2-phenylethanol (Johnston *et al.*, 1980; Tulemonde and Beauverd, 1985). Fröehlich and Schreier (1986) reported headspace and neutral volatiles from litchi fruit imported from South Africa from an unspecified cultivar. Among the volatiles identified, limonene, rose oxide, nonanal, decanal, citronellol and geraniol contributed to the significant fruity-floral and citrus notes of litchi fruit. Twenty-five volatile compounds including an ester, 14 alcohols, two aldehydes, four acids, two ketones and two terpenes were reported in a litchi cultivar from Taiwan (Chyau *et al.*, 2003). Geraniol and geranial were found as major volatile compounds in Taiwan litchi.

Thirteen volatile compounds were detected at harvest: three alcohols, one ester, three monoterpenes and seven sesquiterpenes in cv. 'Mauritius' (Sivakumar *et al.*, 2008b). The cv. 'McLean's Red' showed 19 volatile compounds; four alcohols, three monoterpenes, two oxides and ten sesquiterpenes. In cv. 'Mauritius', alcohols represented 50% of the main fraction, followed by a 23% sesquiterpene fraction, a 21% monoterpene fraction, an unknown component at 6% and ester at 0.7% composition. Esters were not detected in cv. 'McLean's Red'. Among the three alcohols, citronellol and geraniol predominated in the aroma profile of cv. 'Mauritius' and confer a characteristic "floral, rose, citrus and fruity aroma of the litchi fruit" (Chyau *et al.*, 2003). Limonene, rose oxide, citronellol and geraniol were detected at relatively low levels in cv. 'McLean's

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Red' when compared to cv. 'Mauritius'. Rose oxide was not detected in cv. 'Mauritius' (Sivakumar *et al.*, 2008b). Zingiberene was identified as the predominant compound of the seven sesquiterpenes, and terpinolene as an abundant compound among the monoterpenes in cv. 'Mauritius'.

In cv. 'McLean's Red', germacrene D was detected as the predominant compound in the sesquiterpene fraction, followed by muurolene. The germacrene D and muurolene are associated with a woody smell. This showed evidence for the lack of sweet and rose-like fragrance in 'McLean's Red' that supports the consumer demand for the preferred litchi cv. 'Mauritius'. Some of the compounds reported to be responsible for the floral and citrus aromas of litchi fruit – limonene, citronellol and geraniol – were detected at relative low levels in cv. 'McLean's Red' and at higher levels in cv. 'Mauritius'. Fröhlich and Schreier (1986) reported 34 aroma compounds in litchi (cv. not specified) imported from South Africa. Johnston *et al.* (1980) also reported myrcene, limonene, terpinolene, zingiberene, citronellol, nerol and geraniol in an unspecified litchi cultivar. Rose oxide, citronellol, nerol, terpinolene and geraniol were reported in cv. 'No Mai Chi' (Ong and Acree, 1998).

15.3 Production of good quality litchi fruits for postharvest export chain

15.3.1 Importance of fertiliser application to produce good quality fruits

In order to produce good quality fruits for export there must be a good understanding of the importance of fertiliser application and orchard management practices for fruit quality at harvest. Litchi fruit quality is determined by fruit size, weight, colour, taste and flavour. Skin colour, SSC, TA and SSC/TA ratio are generally considered as important quality attributes to determine fruit quality at harvest (Oosthuyse and Westcott, 2005). The SSC, TA and fruit pH affect the taste (sweet-sour) and flavour in many fruits (Auerswald, 1999). The relationship between the nutrition of fruit trees and fruit quality indices has been well documented (Dris *et al.*, 1999). The right nutrient balance is essential to maintain fruit quality. Nutrients with the most notable influence on fruit quality are nitrogen, phosphorus, potassium and calcium (Fallahi and Simons, 1996). Litchi nutrition management is based on monitoring the leaf and soil nutrient levels and adjusting fertiliser practices according to the yields obtained (Menzel *et al.*, 1992; Menzel, 2001). It has been reported that leaf analysis is a useful diagnostic tool for optimising mineral nutrition in fruit trees and that the differences in nutrition correlate well with fruit quality (Fallahi and Simons, 1996), but little is known about litchi fruit quality and nutritional levels. Preharvest fertiliser application also determines the fruit quality at harvest. In South Africa, leaf analysis has been used in nutritional management as reported by the Agricultural Research Council – Institute for Tropical and Subtropical Crops. The optimal leaf norms for 9 to 12 year old trees are N (%): 1.46–1.62, P (%): 0.15–2.0, K (%): 0.90–1.06 and Ca (%): 0.80–2.5.

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Preharvest treatments were tested with commercial practice to improve yield, fruit size, weight and quality attributes of litchi cv. Mauritius. Treatment regimes included, commercial control: T_C = control [30% nitrogen (N) after harvest and 50% flowering, 20% at fruit set; Potassium (K) 40% in March, 60% at flowering; Lime ($CaSO_4$) in March, zinc, boron and copper sprays at flowering]; T_1 = same as T_C but an additional application of low biuret (LB) urea (1%), cytokinin (150 mL/100 L water), (2%) KNO_3 applications; T_2 = as T_1 and auxin, (40 ppm); T_3 = as T_2, replaced auxin with 2% KNO_3 sprays; T_4 = as T_2, auxin and KNO_3 replaced by girdling; $T_5 = T_C + T_1$ + Maxim® + 2% KNO_3 twice + girdling + 2% $CaCl_2$ foliar spray twice (Cronje *et al.*, 2009). Higher fruit firmness and fruit Ca concentration were observed in fruits harvested from trees subjected T_5 with $CaCl_2$ foliar spray at fruit set stage and fruitlet stage. Application of KNO_3 at fruitlet stage in T_1, T_2, T_3, T_5 and girdling practice in T_4 increased the fruit K content and the SSC/TA when compared to the T_C and resulted in a sweet and sour blended flavour that could be regarded as more beneficial for consumer acceptance (Cronje *et al.*, 2009). The T_5 showed an increase in skin redness. This characteristic was shown by the Hunter colour value a*. The a* value increased in T_5 and showed uniform red colour development at harvest. The anthocyanin concentration was higher in fruits obtained from T_5. The uniform red coloured skin has a great impact on consumer acceptance. According to Cronje *et al.* (2009) it is evident that the fruit Ca is important to maintain fruit firmness, colour and K for taste. Skin colour and firmness are important quality attributes that determine consumer acceptance. It is also necessary to balance the K/Ca ratio with fertiliser applications, which depends on fruit and leaf composition analysis. Ascorbic acid levels in fruit are influenced by many factors such as the availability of light to the crop and to individual fruits. Longer day lengths and higher light intensities can increase the concentrations of ascorbic acid and glucose, the precursor to ascorbic acid, in fruit (Lee and Kader, 2000; Mozafar, 1994; Shewfelt, 1990). However, nitrogen or phosphorous tend to decrease ascorbic acid content of fruit, while excess potassium could increase vitamin C content (Nagy and Wardowski, 1998).

Studies showed moderate positive relationships between the proportion of fruit pericarp anthocyanin concentration and leaf K. Also, leaf K correlated positively with titratable acidity as shown in grape fruit (Prange and De Ell, 1997) and deciduous fruit (Du Preez, 1985). A significant positive relationship was reported between the h° of the pericarp and leaf P content (Sivakumar and Korsten, 2007a). An increase in leaf P tends to increase the yellow colour intensity, resulting in a yellowish-pink colour with an increased pericarp h° (Sivakumar and Korsten, 2007a). Therefore, this indicates that moderate or low leaf P content may be the most important cultural practice to obtain good fruit colour in litchi. A strong positive relationship was reported between leaf N and fruit weight and a moderate positive relationship between the leaf Ca and fruit firmness (Sivakumar and Korsten, 2007a). A positive correlation was reported between fruit K and ascorbic acid content (Sivakumar and Korsten, 2007a). Depending on the type of litchi cultivar, consumption of 14–17 litchi fruit would meet the average adult dietary reference intake for vitamin C (ascorbic acid) (Wall, 2006). It should also be noted

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that ascorbic acid content declines during storage. A strong influence of leaf N on fruit weight had been reported earlier (Sivakumar and Korsten, 2007a). However, nitrogen or phosphorous tend to decrease ascorbic acid content of fruit, while excess potassium could increase vitamin C content (Nagy and Wardowski, 1988).

15.3.2 Orchard management

It must be noted that the colour at harvest is an important quality parameter used in selective harvesting. Fruit colour retention after SO_2 fumigation mainly depends on the initial fruit skin colour. Overlapping canopies due to shorter planting distance and a lack of routine pruning practices after each growing season also affect the fruit quality attributers. The shading effect can affect the light radiation on the fruit skin, which is responsible for anthocyanin synthesis (Génard and Bruchou, 1992). Anthocyanin is responsible for the attractive pinkish red fruit skin in litchi. The effect of canopy position on taste components is reported in kiwi (Tombesi *et al.*, 1993), plum (Taylor *et al.*, 1993), peach (Génard and Bruchou, 1992) and litchi (Underhill and Wong, 1990). Litchi fruits exposed to more radiation were observed to have lower SSC/TA ratio (Underhill and Wong, 1990). Ascorbic acid levels in fruit are influenced by many factors such as the availability of light to the crop and to individual fruits. Longer day lengths and higher light intensities can increase the concentrations of ascorbic acid and glucose, the precursor to ascorbic acid, in fruit (Shewfelt, 1990; Mozafar, 1994).

15.4 Constraints during long-term storage and export

Pericarp browning, desiccation, chilling injury, micro-cracking and postharvest decay were identified as major constraints that restrict the expansion of the industry in litchi exporting countries (Huang and Scott, 1985; Li *et al.*, 2001)

15.4.1 Pericarp browning and desiccation

Browning of the pericarp limits the marketability of litchi. This is related to water loss or desiccation from the pericarp (Scott *et al.*, 1982). Wounding or mechanical injury, storage of fruit at undesirable low temperature (chilling injury), pathogen or pest attack (Fitzell and Coates, 1995) and senescence can also result in browning of the pericarp. Browning caused by temperature stress, decay and senescence (Bagshaw *et al.*, 1995) is evident as typical dark and water-soaked areas on the pericarp, whereas browning due to desiccation is differentiated by a pale-dry appearance of the pericarp. According to Huang *et al.* (1990) browning is initiated after harvest, and the pericarp becomes completely brown within three days at room temperature (25°C). Browning initiates from the protuberances of the pericarp and then extends over the entire pericarp surface, until the pericarp eventually becomes dry and brittle (Underhill and Critchley, 1995). Although

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pericarp browning does not affect the eating quality of the aril, it affects the cosmetic appearance of the fruit in the export market.

Intensive research has been conducted to determine the biochemical process underlying litchi browning. Underhill and Critchley (1994) suggested that the pH of the pericarp tissue plays a major role in the browning mechanism. The desiccation or moisture loss from the pericarp tends to increase the pericarp pH (4.15–4.52 over 48 h at 25°C and 60% RH) (Underhill, 1992). Anthocyanins in the vacuoles of the pericarp cells are responsible for the red colour of litchi and their presence is affected by pH change. At higher pH, anthocyanin is converted to a colourless form (carbinol) (Underhill and Critchley, 1994). The pH is the key factor that determines the ratio between the flavylium cation and the colourless carbinol form of the anthocyanin molecules.

The other mechanisms of litchi pericarp browning are mainly attributed to the oxidation process of phenolics, the degradation of anthocyanin by the enzymes polyphenol oxidase (PPO) or peroxidase (POD) (Huang *et al.*, 1990; Underhill, 1992; Zauberman *et al.*, 1991; Zhang and Quantick, 1997) and formation of polymeric browning pigments (*o*-quinones). However, according to Huang *et al.* (1990) the browning was primarily caused by the PPO activity. Since PPO cannot oxidise monophenols or 0-diphenols (Mayer and Harel, 1978) it has been suggested that the POD plays an important role in litchi pericarp browning (Gong and Tian, 2002). Recently, Jiang (2000) reported that litchi PPO cannot oxidise anthocyanin, but that the anthocyanin might be degraded rapidly in an anthocyanin-PPO-phenol system, and suggested that it may be the presence of the sugar moiety that caused steric hindrance. Since anthocyanin is unstable, it could be degraded non-enzymatically or enzymatically. Simpson *et al.* (1976) proposed two possible mechanisms for the non-enzymatic degradation of anthocyanin: (1) the hydrolysis of the 3-glycosidic linkages to produce the more labile aglucone, and (2) hydrolytic opening of the pyrylium ring to form a substituted chalcone. In addition, anthocyanase (anthocyanin-β-glucosidase) also can play a role in removing the sugar groups, leading to anthocyanin decolourisation (Huang, 1995). The PPO activity is also inhibited by antioxidants, such as glutathione and L-cysteine, and activated by divalent cations, such as Mn^{2+}, Ca^{2+} (Jiang *et al.*, 1998; Jiang and Fu, 1999) and SO_2.

The PPO activity was observed to be low at maturity, but an increase in activity occurred during the first two days of storage; however, no significant changes in anthocyanin content were observed during further storage (Underhill and Critchley, 1992; Lin *et al.*, 1998). Although the anthocyanin content did not show significant changes with respect to increased browning (Underhill and Critchley, 1994), according to Zhang *et al.* (2001) the pericarp browning index increased while the anthocyanin content declined during storage. This observation was further supported by Zhang *et al.* (2000) who observed a decline in cyanidin-3-glucoside (major anthocyanin, representing 91.9% of the total anthocyanin) with increasing severity of browning during storage. Jiang and Fu (1999) reported that the moisture loss and increased pH in the pericarp tissue were directly related to the PPO activity. The PPO activity was observed to increase at higher pH (7–7.4)

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and decrease at lower pH, whereas no activity was observed below pH 4.2 (Jiang and Fu, 1997). Underhill and Critchley (1995) concluded that the increase in pH from 4.15 to 4.52 during desiccation was likely to stimulate the PPO activity. The anthocyanins found predominantly in the epicarp and mesocarp of the pericarp and high PPO activity observed in these two layers led to the conclusion that the involvement of PPO activity in desiccation mediated browning (Underhill and Critchley, 1995). In intact tissues, the PPO is separated from the substrate anthocyanin in the vacuole due to compartmentalisation. Water loss or dehydration causes rapid loss of membrane integrity, bringing the PPO into close contact with the substrate (-) epicatechin to initiate the browning reaction. (Jiang and Fu, 1999; Sun *et al.*, 2006). The loss of membrane integrity was observed to be associated with increased electrolyte leakage after harvest and during storage (Zhang *et al.*, 2001).

The PPO activity in cvs. 'Mauritius' and 'Mc Lean's Red' was lower than the POD activity (De Reuck *et al.*, 2009). The PPO activity was higher up to 14 days, and thereafter a decline in PPO activity was observed in both cultivars. The POD activity was low up to 14 days and it increased after 21 days (De Reuck *et al.*, 2009). After finding the higher anthocyanase activity (Zhang *et al.*, 2001) in the litchi pericarp, Jiang *et al.* (2004) suggested from their findings that the anthocyanase catalyses the hydrolysis of sugar moieties from anthocyanins to anthocyanidins and PPO and/or POD oxidises the anthocyanidins. High anthocyanase activity was observed in the litchi pericarp, suggesting the involvement of anthocyanase in pericarp browning, which could be related to the decrease in anthocyanin content in the pericarp during storage. The findings of Jiang *et al.* (2004) suggested that the anthocyanase–anthocyanin–PPO reactions take place in the pericarp cells.

Lin *et al.* (1998) and Underhill and Critchley (1995) have observed increased POD activity during pericarp browning. Furthermore, Tian *et al.* (2002) reported that the partially purified POD rapidly oxidised 4-methylcatechol in the presence of H_2O_2, which supports the involvement of POD in litchi enzymatic browning. Also Zhang *et al.* (2001) reported that POD had a low affinity for anthocyanins. However, in the sequential reactions of POD–phenol–H_2O_2–anthocyanin system, POD catalysed oxidation of guaiacol by H_2O_2, resulting in the formation of quinine followed by anthocyanin degradation. Zhang *et al.* (2001) suggested that in intact litchi pericarp, the accumulation of active oxygen including H_2O_2 was noted and phenols such as catechin and gallocatechin were detected in litchi pericarp. The POD was reported to show different activities towards different phenols. Based on the high POD activity and phenols existing in litchi pericarp Zhang *et al.* (2001) suggested that POD plays a major role in anthocyanin degradation associated with pericarp browning of litchi fruit. Zhang *et al.* (2001) concluded that, although POD could not directly catalyze anthocyanin degradation in the presence of H_2O_2, the anthocyanin could be rapidly degraded by POD when both H_2O_2 and simple phenols, such as guaiacol, were present. The anthocyanidin, resulting from the hydrolysis of anthocyanin, could act as a substrate for POD. According to Zhang *et al.* (2001) the litchi enzymatic browning by POD could involve an anthocyanase–anthocyanin–phenolic–H_2O_2 reaction.

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According to the literature, the differences in browning between cultivars might be linked to differences in oxidation enzyme activities (Ducamp-Collin *et al.*, 2008). Chen *et al.* (2001) reported that PPO activity was higher in cv. 'Nuomici' (browns easily), than in cv. 'Guiwei' (browns more slowly). A similar observation was reported by Ducamp-Collin *et al.* (2008) where the activity of PPO was six times greater in cv. 'Kwai May' than in cv. 'Wai Chee'. In addition the activity of POD was 30 times greater in cv. 'Kwai may' than in cv. 'Wai chee'. In both cultivars, the POD activity was observed to be greater than the PPO activity. Selecting cultivars with good postharvest characteristics such as less browning or susceptibility to browning will be more practical and beneficial for the future.

15.4.2 Chilling injury

Like other tropical fruits, litchis are susceptible to chilling. Depending on the cultivar, temperatures below 0°C or less than 2°C can cause chilling injury. The symptoms can be identified as uniform browning on the pericarp at 0°C, while over 0°C the symptoms are expressed as irregular brown patches. The storage temperature depends on the type of cultivar. The South African cultivars 'Mauritius' and 'McLean's Red' can be stored at 2–5°C. The basic principle behind the browning mechanism due to chilling injury seems to be similar to pericarp browning.

15.4.3 Micro-cracking and fruit cracking

Litchi micro-cracking was reported by Underhill and Simons (1993) who suggested that it is caused by desiccation. The cracking resistant Chinese cv. 'Huaizhi' showed a lower rate of desiccation than the cracking susceptible cv. 'Numici'. Micro-cracking is also one of the causes of pericarp browning (Huang *et al.*, 2004). According to Underhill and Simons (1993) the micro-cracks observed prior to harvest were seen to intensify during storage. Micro-cracking of the pericarp takes place at the initial stage of fruit development due to the rapid expansion of the aril (Huang *et al.*, 2004). According to Joubert (1986) the expanding aril exerts an increased stress or turgor pressure against the pre-grown pericarp, which is composed of three layers: exocarp, mesocarp and endocarp. Drought is another major cause of pericarp cracking during fruit development, which leads to loss of pericarp extensibility (Li *et al.*, 2001). The pericarp structure development was reported for Chinese cultivars ('Huaizhi' and 'Numici') by Huang *et al.* (2004) and South African cultivars ('Mauritius' and 'McLean's Red') by Sivakumar *et al.* (2008b). Micro-cracking can also be caused by handling or packing line operations (Sivakumar and Korsten, 2004).

Litchi cultivars showed similar pericarp development, but differences in the thickness of cuticle and spongy layers were observed between different cultivars (Huang *et al.*, 2004). The spongy tissue responsible for the gas exchange in the pericarp was thought to be responsible for water loss (Lin *et al.*, 1998). However,

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the findings of Huang *et al.* (2004) showed that cv. 'Huaizhi', which had a thicker spongy layer, showed less desiccation. Huang *et al.* (2004) further showed that the cuticle accumulation pattern might help to explain the susceptibility or resistance to micro-cracking in different cultivars. Differences in wax deposit distribution were observed on the pericarp between the developmental stages of South African litchi cv. 'Mauritius' and 'McLean's Red' (Sivakumar *et al.*, 2008b; Sivakumar and Korsten, 2005a). Fruit dropping during the separation process was observed to cause "splitting" damage in the pericarp. Fruit 'cracking' also affects the cosmetic appearance of the fruit in both the domestic and export market. It occurs during fruit development as a result of rapid expansion of the aril, exerting pressure on the pericarp, which has stopped forming new tissue. The degree of severity or damage, depending on the cultivar, is known to intensify with desiccation. The fluctuation of wet and dry periods at late fruit developmental stages can also aggravate fruit cracking. A relationship between fruit cracking and endogenous hormones or mineral nutrition (Ca, Mg and B) was reported by Qui *et al.* (1999) in cv. 'Numici'. The contribution of calcium to cracking resistance is related to its structural role in the cell walls, and the availability of calcium during early fruit development is important for cracking resistance. Huang *et al.* (2005) and Peng *et al.* (2004) also reported that fruit cracking could be reduced by foliar application of brassinolide, a plant growth activator, before blossom, which could be recommended as a standard commercial practice, also to increase its commercial fruit value.

15.4.4 Postharvest decay

Microbial ecology of litchi

Large numbers of different microbial species are associated with crops throughout their life cycle. The majority of these organisms are natural epiphytes, whereas only a small percentage are pathogens, with the ability to parasitise the host. Saprophytes feed on decaying material and therefore dominate on older senescing plant tissues, forming a particular ecological balance together with epiphytes and pathogens (Sobiczewski *et al.*, 1996). Different microbial species are associated with each fruit development stage and are influenced by prevailing environmental conditions (Teixidó *et al.*, 1999). The epiphytic microflora of the litchi fruit predominantly consist of fungi, which can be attributed to the acidic pH of the rind (De Roever, 1999). Microbial population dynamics can be influenced by external interferences in the ecosystem, resulting in temporary or permanent niche displacement (Korsten, 2006). Extrinsic (environmental) factors imposed on plants influence the survival and growth of epiphytic microflora. Both extrinsic and intrinsic parameters (such as the nature of the epithelium and protective cuticle, tissue pH, phytoalexins and the presence of antimicrobials) determine the types of microorganisms that will colonise or infect the fruit (Beuchat, 2002). The presence of soil or faecal material on the surface of produce, that may permeate cut tissue, could alter the ecological environment as well as the behaviour of

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pathogens and other microflora (Beuchat, 2002). Insects play a vital role in the dissemination of microorganisms on fruit surfaces. Fruit flies carry yeasts between fruit surfaces, and the growth of osmophilic yeasts protects the fruit from invasion by other microbes. Unsaturated fatty acids produced by yeasts may inhibit development of Gram-positive bacteria on fruit surfaces. Bacterial populations that develop on fruit surfaces are dependent on growth factors, such as thiamine and nicotinic acid that are produced by yeasts. Yeast populations are also dependent on growth factors produced by bacteria on fruit surfaces (Atlas and Bartha, 1998). Once a fruit is harvested, the stable microbial population starts to change. Each step in the postharvest chain can have an impact on the total microbial population (Korsten, 2006).

The microbial population dynamics on litchi fruit surfaces are most severely affected by SO_2 fumigation, which is used commercially due to its ability to eliminate all microbial growth on the fruit surface (Korsten, 2006). However, dehydration of the litchi pericarp and the formation of micro-cracks on the fruit surface leave the fruit vulnerable to infection by opportunists in the export chain (Sivakumar and Korsten, 2005b). Of interest was the significant increase in opportunistic pathogens such as *Phomopsis, Aspergillus* and *Penicillium* spp. after SO_2 treatment, as documented by De Jager *et al.* (2003). These pathogens, particularly *Penicillium* spp., are of major economic importance in the litchi industry, resulting in high annual losses on export markets (De Jager and Korsten, 2003).

Postharvest pathogens affecting litchi

Preharvest parameters that promote and facilitate infection of litchi fruit by *Penicillium* species include environmental factors such as warm winds (to facilitate spore dispersal), high rainfall and pest damage (De Jager *et al.*, 2003; Jiang *et al.*, 2003). Environmental conditions, extensive exposure of the fruit to harsh sunlight and pest infestation may cause the pericarp to be desiccated, damaged or cracked (Gilbert, 1978). Desiccation of the fruit associated with mycological decay as micro-crack formation is initiated in the pericarp. These micro-cracks, as well as lenticels, stomata and associated pericarp damage, serve as entry points for pathogens (Sivakumar *et al.*, 2005b). *Penicillium* species are one of the most dominant decay causing agents affecting litchi fruit. The litchi pericarp provides an ideal environment for conidial attachment and fungal growth, even under cold storage conditions (Underhill and Simons, 1993). The numerous protrusions on the litchi pericarp give it a particularly rough texture (Sivakumar *et al.*, 2005b), whereby conidia require minimal energy to attach to the fruit. Distinguishing between healthy and *Penicillium* infected fruit may be difficult during preharvest growth development as micro-cracks are difficult to detect (Coates *et al.*, 1995). The litchi pericarp is only 1–3 mm thick (Underhill and Simons, 1993) and the flesh of the fruit provides an abundance of nutrients and sugars as well as a low pH, which selects for fungal growth, in particular that of *Penicillium* species (Lichter *et al.*, 2004; Tournas *et al.*, 2005).

Penicillium is one of the most commonly known storage fungal species. Primarily, contamination of litchi fruit occurs during storage, with potential for

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growth and development of the fungus during storage and transport. Following fruit harvest, the microbial population of the phylloplane is altered (Korsten, 2006). As *Penicillium* is an opportunistic pathogen, it will thrive and develop rapidly, and the microbial balance of the fructoplane changes due to postharvest treatments such as SO_2 fumigation (Korsten, 2006). The South African litchi export chain takes about 30 days to reach European destinations. During this process the litchis are subjected to the development of superficial mould growth, which can render a whole consignment unmarketable (Swarts and Anderson, 1988). In some litchi exporting countries such as Israel and South Africa, the fruit are subjected to an HCl dip after SO_2 fumigation in order to regain the natural reddish colour of the litchi skin. The acidification process creates a niche that is selective for *Penicillium* growth and dominance (Zhang *et al.*, 2005; Coates *et al.*, 2005).

Postharvest decay of litchi by *Penicillium* spp. manifests itself as a blue-green powdery mould growth on the fruit pericarp, followed by softening of the fruit (Coates *et al.*, 2005). *Penicillium* conidia are very resistant, lightweight and have the ability to survive in sub-optimal conditions. The factors that favour the establishment of *Penicillium* spp. on the fruit surface include (1) the high efficiency of spore attachment, (2) extended viability of the spores, (3) colonisation on most surfaces and (4) easy distribution of spores via air circulation between fruit (Morey *et al.*, 2003; Anderson, 1954). In favourable conditions, the spores germinate immediately and the mycelia penetrate the flesh of the fruit (Anderson, 1954). Environments with a high RH, such as packinghouses, provide suitable conditions for the growth and spread of *Penicillium* spp. (Johnston *et al.*, 2006). *Penicillium* is commonly known as a soil inhabitant and its presence in other environments may serve as an indicator of poor hygiene quality and cross-contamination (Johnston *et al.*, 2006; Fitzell and Coates, 1995). Johnston *et al.* (2006) identified several *Penicillium* spp. in packhouses, ports and repacking facilities during export chain trials, indicating that cross-contamination of the fruit may occur at any stage during the entire litchi production and export chain (Johnston *et al.*, 2006; Jacobs and Korsten, 2004; Tournas and Karsoudas, 2005). The predominant *Penicillium* spp. throughout the litchi export chain was identified as: *P. expansum, P. griseofulvum, P. spinulosum, P. brevicompactum, P. corylophilum, P. verrucosum, P. aurantiogriseum, P. sclerotiorum, P. glabrum, P. solitum, P. citrinum, P. chrysogenum* and *P. crustosum* (Johnston *et al.*, 2006). The presence of *P. verrucosum* and *P. expansum* is of great concern, due to the ability of these pathogens to produce mycotoxins, such as Ochratoxin A and Patulin, posing health and safety risks to the consumer (Johnston *et al.*, 2006).

A number of other postharvest pathogens are also known to affect litchi. Anthracnose, caused by *Colletotrichum gloeosporioides*, is one of the most common diseases affecting litchi after harvest. The symptoms of anthracnose manifest as circular dark-brown to black lesions on the fruit, with salmon-coloured spore masses produced under humid conditions (Coates *et al.*, 2005). Infected leaves and stems act as principal sources of inoculum for the spread of this disease (McMillian, 1994). Conidia are spread by water drops and require free water or

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wounds for infection. Infection occurs by direct penetration of the fruit skin or flesh. Immature fruit can be infected in the orchard, but the pathogen numbers are low and the spores remain dormant until fruit ripening and senescence, after which symptoms will start to manifest. High temperatures after harvest favour disease development (Coates *et al.*, 2005; McMillian, 1994).

Stem-end rot is caused by a number of fungi. While symptoms vary with the causal agent, the rot generally appears as a browning of the skin at the stem-end of the fruit. Lesions expand rapidly, particularly those caused by *Lasiodiplodia theobromae*. Under humid conditions, the surface of the lesions may be dotted with numerous black pycnidia. *L. theobromae, Phomopsis* spp. and anamorphs of *Botryosphaeria* spp. are the most common infective agents (Johnson, 1990). The main modes of infection are thought to occur through the cut or damaged surface of the fruit pedicel or endophytic colonisation of the fruit pedicel at the stem-end (Coates *et al.*, 2005). *L. theobromae* survives in orchards on dead twigs, leaves, branches and infected fruit. The lesions on the fruit spread rapidly and eventually cover the entire fruit. In advanced stages of infection the affected areas are covered with many black pycnidia. The flesh becomes shrivelled and discoloured in severely affected fruit. Conidia are spread by water, with infection occurring through wounds or natural openings. Incidence of fruit rot can be reduced by reducing the amount of inoculums in an orchard, through pruning of dead wood and removal of infected fruit.

Peronophythora litchi (Chen, 1961; Ko *et al.*, 1978) infection affects the immature and ripe fruit, as well as leaves and inflorescence in China, Taiwan, Thailand and in Vietnam (Vien *et al.*, 2001). The disease of *P. litchi* is favoured by cool wet weather during fruiting and flowering. The pathogen enters the host by direct penetration by zoospores, with incubation less than 1 day at 25°C (Chi *et al.*, 1984). Pepper spot caused by *C. gloeosporioides* affects litchi in Australia (Drew and Drew, 1999). The disease causes superficial blemishes and affects the cosmetic appearance of the fruit. The symptom manifests as pinhead-sized dark spots that develop on the stem-end and shoulders of the fruit (Bagshaw *et al.*, 1995). Conidia produced on infected leaves and fruit are the principal source of inoculums and warm, wet weather favours infection and spread of the disease.

Fungi isolated from the South African packhouses, such as *Alternaria* spp. (greenish brown rot), *Penicillium* spp. (blue mould), *Rhizopus* spp. (rhizopus rot) and several species of *Aspergillus, Phoma*, and *Fusarium* are responsible for postharvest decay in litchi (De Jager *et al.*, 2000). Disease incidences of blue mould and rhizopus rot have been implicated due to insanitary conditions in the storage environment or contaminated equipment resulting from infected or rejected fruit (Fitzell and Coates, 1995).

15.4.5 Foodborne pathogens

An increase of foodborne diseases from fresh fruit and vegetables have been linked to an increased consumption of these commodities in recent years. Millions

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of people suffer from diseases that can be traced back to contaminated food. A number of factors have been identified that influence produce-linked outbreaks such as: (i) the increasing trend to centralise production and distribute produce over greater distances, (ii) importing fresh produce from abroad, (iii) increased worldwide consumption of fresh fruit and vegetables, (iv) increased exposure of people to new pathogens through global trade and international travel, (v) inappropriate storage and handling practices in food preparation areas and (vi) improved scientific identification methods to track the source of pathogens. These changes could have an important effect on the ecological behaviour of pathogens and spoilage microorganisms on fresh commodities, resulting in an increased risk of human diseases (Beuchat, 2002).

Several foodborne pathogen outbreaks have been associated with fresh and processed fruit. *Salmonella* spp., *Shigella flexneri, Vibrio cholera*, viruses and protozoan parasites have been isolated from watermelon, cantaloupe, fruit salad, coconut milk, fresh and frozen strawberries and raspberries (Gaylor *et al.*, 1995; Herwaldt and Ackers, 1997). No disease outbreaks have been linked to litchis yet. However, the uneven litchi pericarp and micro-cracks, exposing the fruit flesh, provide ideal surfaces for the attachment of foodborne pathogens, and future research needs to focus on the attachment, colonisation and survival of foodborne pathogens on the litchi fruit surface.

Foodborne and postharvest pathogens may infect litchi fruit through micro-cracking of the pericarp, microscopic bruises, cuts and punctures inflicted by mechanical injuries during handling or microscopic wounds in the pericarp made by fruit flies (Janisiewicz *et al.*, 1999; Sivakumar and Korsten, 2005b). Janisiewicz *et al.* (1999) demonstrated the transmission of enterohaemorrhagic *Escherichia coli* O157:H7 by fruit flies and the exponential growth of these bacteria in wounded apple tissue (Janisiewicz *et al.*, 1999). Wells and Butterfield (1999), however, concluded that wounding is not essential for *Salmonella* proliferation on several commodities and that certain fungus may stimulate growth of *Salmonella enterica* subsp *enterica* serovar Typhimurium (Wells and Buterfield, 1999).

A study by Sivakumar and Korsten (2005b) indicated that micro-cracks were more evident on SO_2-fumigated fruit in which fungal sporulation structures were observed. The micro-cracks could provide ideal sites for the attachment of foodborne pathogens as well. During handling, pathogens can be introduced, thereby colonising and multiplying on the fruit surface. Several preventive measures can be put in place to prevent the infection and spread of disease-causing microbes on fresh produce. One of these systems includes the implementation of HACCP. Fruit handlers suffering from any disease (e.g. diarrhoea) that could potentially be transmitted through fruit should not be permitted to come into direct or indirect contact with fruit (De Jager *et al.*, 2000). Contamination may be introduced where workers do not have access to sanitary facilities or do not practise proper personal hygiene (Adams and Moss, 2000). Microorganisms, ubiquitous in and on the human body (Murray *et al.*, 1995), have been isolated, and can be readily transferred onto operating surfaces and to fruit. Nasal carriage of *Staphylococcus aureus* can be transmitted between humans as well as onto

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produce that is manually handled by infected persons. Approximately 20% of healthy individuals are estimated to be persistently colonised by *S. aureus*, while as many as 60% can be colonised intermittently (Kluytmans *et al.*, 1997). However, since *S. aureus* was detected in the litchi postharvest chain in 2005 (unpublished information), the importance of personal cleanliness and the provision of clean and hygienic ablution facilities at farms and packhouses as well as protective clothing and the practice of effective sanitation procedures need to be enforced (De Jager *et al.*, 2000).

The physical design of packing sheds, processing plants and related facilities should also be taken into consideration (De Roever, 1999; Brackett, 1999; Adams and Moss, 2000). Sorting and grading of harvested fruit should take place in shaded and well-ventilated areas or in temperature-controlled packinghouses (Holcroft *et al.*, 2005). Although sorting and packing areas appear clean superficially, high total microbial counts have been detected in these seemingly clean environments (De Jager *et al.*, 2000). Unhygienic packinghouse and cool storage conditions where rotten fruit is not regularly removed contribute to continuous product contamination. De Jager *et al.* (2000) determined the sanitation levels in packhouses, at different packline stations including crates at collection points, the dumping tank, air quality around the drying tunnels, off-loading area, surface of the brushes and sorting rollers, sorting and packing conveyor belts, and air quality surrounding the packline. It was concluded that significantly higher microbial densities occurred on packline surfaces and in the dumping tank than those found in air samples of drying tunnels and surrounding the packlines (De Jager *et al.*, 2000). Fitzell and Coates (1995) recommended that packhouse equipment be either steam-cleaned (+ 110°C) or cleaned with high-pressure hot water sprays (6800 kPa, >75°C), followed by the application of sanitisers (Fitzell and Coates, 1995).

Depending on the designated market, transport of litchi can occur via land, sea or air. Loading dock workers, truck drivers and retail workers are important role players in preventing cross contamination of produce and maintaining correct temperatures during distribution. Shipped produce is stored in refrigerated trailers that rely on proper air circulation to maintain temperatures throughout the trailer. Obstruction of air circulation will reduce or prevent appropriate cooling, thereby enhancing pathogen survival and growth. Although no reports found to date can claim that fresh litchis are the source of foodborne illnesses, the litchi industry should be proactive in investigating microbiological safety.

15.5 Postharvest picking, in-field sorting and transport

The early season fruit are harvested selectively to ensure that only mature fruit are marketed (Lemmer and Kruger, 2002). Thereafter, picking is carried out repeatedly at regular intervals. During the peak of the harvest season fruit are harvested as clusters with the panicle at uniform maturity (see Fig. 15.1). Fruit are generally handpicked using ladders. They are harvested during the early morning in order to

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Fig. 15.1 Harvesting litchi.

prevent moisture loss and associated weight loss, and the panicle is separated from the tree branches by cutting or twisting the panicles. Thereafter individual fruit is removed from the panicles by a secatier. When removing the fruit from the tree directly, about 3 mm of the pedicel is left on the fruit in order to prevent skin splitting. Litchi fruit has to be harvested prior to extreme day temperatures that occur from late morning to early afternoon. It is shown from the fruit water potential that a rapid loss of turgour occurs early in the morning (~8 am), with a recovery in the afternoon (~4 pm) (Olesen et al., 2003). The loss of turgour can affect the fruit weight (Olesen *et al.*, 2003), with negative financial implications. Research also showed the potential of rehydration of the fruit after harvest to prevent or reduce the browning process. The capacity of fruit rehydration was observed to reduce during the first hour following harvest (Olesen *et al.*, 2003). It remains a question whether rehydration can be used commercially, as the duration from harvest to delivery to the packhouse may take longer than 1 h. Maturity standards for harvesting for each cultivar must be adopted according to maturity standards developed, which depend on growth conditions and climatic factors. Ripeness standards in terms of SSC/TA also affect the postharvest performance with respect to different technologies.

The fruit separation from the panicle is carried out in the field under shade and fruit are collected in clean plastic crates. Rapid transfer of fruit from the orchard to the packhouse is recommended to retain the postharvest quality during storage. Fruit has to be handled with care in order to prevent mechanical damage during harvesting and postharvest handling. Generally fruit are not harvested during

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rainy weather. After harvest the loaded vehicle has to be kept under shade and during transport the vehicle has to be covered with light coloured tarpaulins or canvas or wetted hessian to prevent heating, sun injury and premature browning.

15.6 Postharvest chain and packhouse treatments

15.6.1 Sulphur dioxide fumigation

The litchi industry commercially uses SO_2 fumigation to overcome the postharvest browning and infection by postharvest pathogens (Swarts, 1983). Fumigation is achieved by burning 100 g of 90% sulphur powder per m^3 of fruit at room temperature (25–28°C) for 20 min with no humidity control (Holcroft and Mitcham, 1996). In Israel and South Africa, SO_2 fumigated fruit is subjected to dipping in diluted HCl to restore the red colour following SO_2 bleaching; this practice has gained commercial acceptance (Jiang and Fu, 1999; Zauberman *et al.*, 1990). The SO_2 is thought to be an inhibitor of PPO (Fuchs and Zauberman, 1993) and SO_2 treatments reduced browning. It is reported in the review written on litchi by Holcroft and Mitcham (1996) that the SO_2 and anthocyanin form an anthocyanin–SO3H complex that is more stable, and effects of SO_2 may be the result of this complexing rather than PPO inhibition (Underhill and Critchley, 1992; Underhill and Simons, 1983). If excess sulphur is used, the fruit turns yellow or pale green and fails to return to the original pinkish red colour. Sulphite bleaching occurs as the negative ions from the sulfurous acid attack the flavylium cation and form chromen-4 (or 2)-sulfonic acid (Timberlake and Bridle, 1967).

The SO_2 fumigation imparts a yellow colour to the fruits (see Plate XXVII). However, the original red colour of the pericarp is regained in a matter of weeks during storage (Fig. 15.2). Hydrochloric acid (HCl) dip treatments, followed by SO_2 fumigation, help rapidly to restore the red colour (Zauberman *et al.*, 1990). The pericarp pH was reported to range from 2.6 to 3.0 in SO_2-HCl treated fruits (Lichter *et al.*, 2004). Therefore, the acidic pH helps to retain the flavylium form stable, in order to regain the red colour of the litchi pericarp. One of the main concerns with SO_2 fumigation is that it leaves undesirable residues (Kremer-Köhne, 1993). In recent years there have been growing concerns regarding SO_2 residue levels present in the fruit, especially by importing countries in Europe, and in the US and Japan. At present, the strict standards enforced on fruit imports by the European Union permit a maximum concentration of sulphur residue levels of only 10 $\mu g\ g^{-1}$ in the edible portion of the fruit (Ducamp-Collin, 2004).

15.6.2 Undesirable effects of sulphur dioxide fumigation on litchi fruit quality

Fumigation with SO_2 causes undesirable effects on fruit quality. The fruit taste is altered due to higher titratable acidity and lower pH resulting from direct penetration of SO_2 through the skin into the aril (Lonsdale and Kremer-Köhne, 1991; Tongdee, 1993). Evaluation of SO_2 fumigated fruit of different cultivars

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Fig. 15.2 Sulphur dioxide fumigated fruit after 21 days' storage (cv. 'Mauritius').

indicated a 12–14% mass loss during low temperature storage at 2°C (Lemmer, 2002; Sivakumar and Korsten, 2006a). It is also evident that commercial SO_2 fumigation intensified micro-cracking of the pericarp (Sivakumar *et al.*, 2005b). Similar observations on grapes were reported by Zhang *et al.* (2003). The SO_2 fumigation also results in health hazards for packhouse workers and consumers, causing allergic reactions and respiratory problems (Koeing *et al.*, 1983).

The build-up of SO_2 residues in the pericarp and aril is dependent on different factors, such as damage to the pericarp RH and storage temperature. According to Lemmer (2002) the SO_2 residue levels in the pericarp and aril (edible portion) of six cultivars ('Wai Chee', 'Fay Zee Siu', 'Kwai May Pink', 'Haak Yip', 'HLH Mauritius' and 'McLean's Red') were observed to be 1000–1400 $\mu g\ g^{-1}$ in the pericarp and 10–14 $\mu g\ g^{-1}$ in the aril soon after SO_2 fumigation and declined to 200–250 $\mu g\ g^{-1}$ and 8–12 $\mu g\ g^{-1}$ respectively during low temperature storage at 1°C. The detected SO_2 residues varied between cultivars: higher values were recorded in cv. 'McLean's Red' than in cv. 'Mauritius'. Kremer-Köhne (1993) concluded that the different residue levels in the two cultivars could be due to differences in the permeability of the skin. However, the surface electron microscopic description of the two cultivars shows more wax deposits and cuticular ridges on the pericarp surface of cv. 'McLean's Red' than of cv. 'Mauritius' (Sivakumar *et al.*, 2008b). Furthermore, higher SO_2 residues were reported in the arils of fruit of cv. 'McLean's Red' and 'Mauritius' subjected to an acid dip treatment following SO_2 fumigation. Lemmer and Kruger (2000) also explained that peel injury caused by a low pH treatment could facilitate an increase diffusion rate into

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the aril, leaving less residue in the peel and consequently higher residues in the aril. The storage temperature and RH also influenced the movement and absorption of SO_2 in the fruit, while higher storage temperatures with low RH favoured the build-up of SO_2 residues in the aril (Lemmer and Kruger, 2000). The time lapses between harvesting and fumigation also influenced the SO_2 residue build-up in the aril (Lemmer and Kruger, 2000). It is also evident from the investigations that as the time lapse increased, the SO_2 residues also increased. In the case of the 10 h and 18 h regimes, unacceptably high values were obtained in the aril after 25 days of cold storage (Lemmer and Kruger, 2000). At 3 h regime, the residue was within the 10 ppm limit (Lemmer and Kruger, 2000). Therefore, it is clearly evident that the time lapse between harvesting and fumigation must be kept to a minimum. All these undesirable effects of SO_2 fumigation have necessitated the development of alternative postharvest treatments to maintain overall quality during storage and transportation. After SO_2 fumigation, *Penicillium* spp. can become a major problem in the litchi export industry (Jiang *et al.*, 2003). It is also known that SO_2 fumigation affects the natural ecological balance and enhances decay due to saprophytic postharvest colonisation of *Penicillium* spp. (De Jager and Korsten, 2003).

Free water on the fruit surface interferes with SO_2 function. Wet fruit should be air-dried before fumigation. Fumigation rates vary greatly with the maturity stage of the harvested fruit: younger fruit requires lower dosages than mature fruit. Fumigation rates also vary greatly with cultivar types (Kremer-Köhne, 1993). According to Tongdee (1993) in Thailand, cv. ‘Kom’, a dark-coloured, pointed spiked cultivar requires an application rate about twice as high as ‘Hong Huai’, a light red, smooth thin-skinned cultivar. It is also noted that SO_2 injury symptoms occurred when fruit was fumigated at too low a dosage. Symptoms of SO_2 injury (irregular brown lines or patches on the interior of the rind) were commonly observed at the stem-end especially in over-matured fruit, or thick-skinned or dark-coloured cultivars. This is likely to be due to the characteristics of the skin: the thickness, texture and the concentration of anthocyanin. Therefore, dosage of one cultivar may not be suitable for others.

15.6.3 SO_2 fumigation procedure

The SO_2 fumigation is carried out in fumigating chambers. The fumigation can be done with compressed gas (vaporising liquid SO_2) injected directly into the sealed fumigation chamber. Alternatively sulphur powder can be burned to produce SO_2 gas. At present all the packhouses in South Africa use a solid chamber structure with a tightly sealed door. If sulphur powder is used, it is placed in small trays between the stacked crates in the spaces left for ventilation. After fumigation the residual SO_2 is removed from the chamber. Generally after SO_2 fumigation sorting is carried out to remove all remaining low quality fruit including SO_2 burned fruit. In order to ensure the movement of the SO_2 within the fumigation chamber, the chamber must be filled to half to two-thirds of the total volume of the chamber. Generally fans are fitted inside the fumigation chamber to ensure even distribution of SO_2 gas within the chamber. Furthermore, calibration of the fumigation unit

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is very important. The quantity of SO_2 absorbed by the fruit is dependent on the quantity of SO_2 that was in contact with the weight of fruit in the fumigation chamber. At the same time the concentration of the SO_2 in the air around the fruit is dependent on the amount of sulphur powder burned or the SO_2 gas released from the compressed cylinders. According to the available reports, SO_2, concentration 0.107 g per litre free space in the fumigation chamber is sufficient to reach the residue limit of 10 μg g^{-1} in the edible portion after 25 days' cold storage (Lemmer and Kruger, 2002).

15.6.4 Use of HCl dips

The HCl dip treatment is adopted to restore the SO_2 bleached fruit to their original red colour. Although the SO_2 fumigation and low pH technology (Zauberman *et al.*, 1990) were developed in Israel some producers have incorporated this treatment in their packhouses in South Africa. However, the usage of this technology had been restricted due to the increasing concern over the use of chemicals on fresh produce, and France has discontinued importation of litchi subjected to SO_2-low pH technology and the US has phased out the use of HCl on litchi fruit. The standard treatment in South Africa is to apply HCl (pH 0.9–1) as dip treatment for 4–8 min and the colour change becomes more prominent after 24 days cold storage. The intensity of the red colour of the pericarp can be increased by increasing the exposure time to 8 min. However, with increasing exposure time loss of fruit firmness and higher incidence of *Penicillium* decay was observed during long term storage.

15.6.5 Use of metabisulphite salts

The effect of sodium metabisulphite impregnated sheets (SMS-sheets) on decay control and browning inhibition was shown by Schutte *et al.* (1990) on two South African litchi cultivars ('Mauritius' and 'Madras'). Cultivar 'Mauritius' was exposed to slow (350 mm × 217 mm; 0.010 g SMS) and fast-releasing type (377 mm × 217 mm) SMS-sheets, placed around the fruit inside polyethylene bags (without perforations). The cv. 'Madras' was packed in a similar way, but double phase type SMS sheets (0.55g SMS) were used to release the SO_2 over a longer period. After 21 days' storage at 3.5°C, the study indicated that the two slow-releasing SMS-sheets on the outer edge of the fruits inside polyethylene bags resulted in 100% decay control and 2% pericarp browning. In combination with a fast-releasing SMS-sheet, 90% of the fruits were marketable, but browning increased to 9%. Similar observations were reported by Schutte *et al.* (1990) on cv. 'Madras' with slow-releasing SMS-sheets at increased SMS concentration. However, the higher concentration of SMS used in cv. 'Madras' became a limiting factor to commercialising this technology. Furthermore, the fruit quality was retained only up to 21 days' storage.

Integrated treatments with sodium metabisulfite and HCl dip significantly reduced litchi browning and decay during 28 days cold storage. According to

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Duvenhage (1996) this treatment resulted in significant weight loss and altered taste in 'Mauritius' and 'McLean's Red' cultivars.

15.6.6 Packing line operation and cold chain management

Sorting and size grading

Sorting can be done under shade or in temperature controlled packhouse sorting lines. In South Africa fruit are sorted in terms of size. Export fruit must have a minimum diameter of 30 mm. The quality criteria include dark blemishing, insect damage, torn fruit, undeveloped and double fruit, fungal infected fruit and incomplete sulphured fruit. Most packhouses have a mechanised grading packing line facility. The Food and Agriculture Organization of the United Nations has developed CODEX quality standards for fresh litchi. According to the CODEX standards (2005), mature fruit must have a predominantly red pericarp with only a small area of green; the diameter of the fruit must be larger than 20 mm for standard or second class (classes 1 and 2) fruit; and 33 mm for 'Extra' (Superior) class fruit (CODEX standards, 2005). The SSC must be greater than 18% and the residue for sulphur in the flesh should not exceed 10 $\mu g\ g^{-1}$ (Mitra, 2006).

Temperature management

Postharvest handling strategies have to be improved throughout the system, i.e. from harvesting practices, time of harvest, pre-cooling, packing line operations and cold chain management, through to the end consumer. Most importantly, the cold chain has to be maintained in order to ensure superior fruit quality. Litchi fruit has to be pre-cooled immediately after harvest to remove the field heat and provide an effective cold chain management system during storage and transportation (Ketsa and Leelawatana, 1990; Lin and Chaiang, 1988). Hydrocooling at 0–2°C is recommended for litchi fruit and it is the most rapid cooling method that brings the pulp temperature to 2–3°C within 10–20 min. However, fruit must be dried prior to packing after hydrocooling, as presence of water droplets on the fruit surface can enhance decay development during storage and transportation. Hydrocooling is not recommended for litchi that will be subjected to SO_2 fumigation. Forced-air cooling was also recommended, which will become effective when the cold room has humidifiers to maintain ~ 90% humidity to prevent desiccation during the forced-air cooling process. According to Holcroft *et al.* (2005) forced air cooling with 2.5 cm static pressure difference at 3–5°C and a 80–90% RH took 60 minutes to achieve the desired pulp temperature. Cold storage enables decreasing of the oxidising enzymes (PPO and POD) activities and also by reducing the rate of respiration. It reduces the changes in TSS/TA ratio and also the loss of ascorbic acid concentrations and prolongs the shelf life up to seven to ten days. Generally room cooling at 2°C air temperature and 80–90% RH reduces the pulp temperature to 2°C within 13–14 h. According to Moreuil (1973), litchi fruit hydrocooled at 0–2°C after harvest, packed in sealed polythene bags and stored under low temperature storage

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retained the pericarp colour for a month. Storage temperature for litchi can vary from 2–7°C.

15.7 Developments in postharvest technologies to replace sulphur dioxide fumigation

15.7.1 Gamma irradiation

Irradiation in combination with low temperature storage may be recommended as an alternative to SO_2 fumigation during short-term storage (less than 10 days) (Ilangantileke *et al.*, 1993). Irradiation treatment showed differential responses with respect to cultivar and dosage. According to Ilangantileke *et al.* (1993), irradiation up to 1 kGy dose, in combination with low temperature storage, maintained the market quality of Thai litchi by reducing the loss of red colour of the pericarp and fruit rot. However, it failed to retain the overall fruit quality during long term cold storage. The irradiation is not a commercial practice in many countries for fresh produce due to the negative perception of consumers, regarding the safety of irradiated food for consumption (Jiang *et al.*, 2003). Since it is ineffective in retaining the quality attributes of litchi during long term storage exceeding 16 days, irradiation cannot be implemented commercially as an alternative or as a partial alternative to replace SO_2 fumigation (Ilangantileke *et al.*, 1993). Fruit packed in Vita film and thereafter irradiated at 0.75 kGy or 1.5 kGy are more susceptible to decay development after storage than untreated fruit due to irradiation damage on the pericarp (Lonsdale, 1993).

15.7.2 Postharvest dip treatments

Application of different postharvest treatments was investigated to increase the storage life of litchi fruit at low temperatures (2–5°C). Polyamines were observed to retain the red colour of the pericarp at low temperatures up to 30 days in storage (Jiang and Chen, 1995). Polyamines such as putrescine, spermine or spermidine at concentrations 1 mmol L^{-1} in combination with fungicides were reported to delay or reduce ethylene production, peroxidase activity and also retain membrane integrity that ensured the separation of enzyme and substrates. However, the litchi importing countries are moving towards minimal fungicide use on fruits, due to the negative impact on consumers and the environment. Combined application of glutathione and citric acid was also reported to reduce the browning of pericarp by inhibiting the polyphenol oxidase activity (Zhang *et al.*, 2001). However this application was effective in controlling browning in storage for up to four days.

Chitosan (1%) dip solutions in acetic acid showed beneficial effects on cv. ‘Huaizhi’, such as delaying changes in the concentration of anthocyanin, flavonoid, total phenolics, and reduced the PPO activity or inhibited the increase of POD activity, thereby reducing the severity of browning under low temperature storage (4°C) (Jiang and Fu, 1999). In cv. ‘Mauritius’, chitosan at 0.1% concentration reduced microbial decay and the fructoplane microbial

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population (Sivakumar *et al.*, 2005b). Chitosan inhibits the growth of decay causing fungi and induces a defensive response in host tissues. It is hypothesised that chitosan coating forms a filmogenic coating (Zhang and Quantick, 1997) around the fruit to modify its endogenous CO_2 and O_2 levels, that could result in a reduced supply of oxygen for the enzymatic oxidation reaction of the anthocyanin. The observation on reduced respiration in chitosan coated (2%) cv. 'Huaizhi' litchi was reported by Jiang *et al.* (2005). Chitosan coating, integrated with acidification, formed an acid coat that further stabilised the acidification of the pericarp (Joas *et al.*, 2005). However, when the fruit were transferred from cold storage to market shelf conditions at 25°C, the litchi pericarp turned brown, losing its visual quality. It is also reported that application of 2% chitosan coating soon after cold storage extended the shelf life of litchi fruits for 12 h at 25°C (Jiang *et al.*, 2005). Furthermore, dipping the fruit in chitosan coating after cold storage protected the litchi pericarp from browning and decay and retained the physico-chemical properties of the edible portion. Cultivar dependent response to chitosan treatment was reported by Ducamp-Collin *et al.* (2008). Cultivar 'Kwai May' was better suited to chitosan citric acid treatment than cv. 'Wai Chee'. This clearly showed that different cultivars responded differently to the chitosan dip treatment. Although chitosan solution was prepared in different acids (citric acid, oxalic acid and tartaric acid), acetic acid was used to prepare the solution, since it is the best acid to activate chitosan's antimicrobial and eliciting properties to prevent decay (Romannazi *et al.*, 2005). However, none of the dip treatments retained the overall fruit quality for more than 21 days in cold storage.

15.7.3 Heat treatments

Litchi fruit exposed to steam treatment at 98°C for 30 s followed by hydrocooling in distilled water at pH 0 for 5 min retained the red colour of the pericarp during storage. However, this technology failed to achieve commercial acceptance since the steaming process affected the edible portion (aril) of the fruit (Kaser *et al.*, 1995). This treatment was improved by reducing the steam treatment to 2 s, cooling in water at pH 0 and coating the fruit with 1% Vapogard® (di-1-P menthene; Hygrotech Seed, Pty Ltd, Pretoria, South Africa) an anti-transpirant, which retained the red colour of the pericarp without discolouration of the aril. It is also reported that co-pigmentation or complexing of anthocyanin might increase the stability of the pigment. However, the steam treatment failed to show the direct evidence of co-pigmentation and the observation on red colour retention could be due to the direct effect of pH (Holcroft and Mitcham, 1996).

Vapour heat treatment at 45°C (core temperature) for 42 min was reported to maintain the quality of cv. 'Tai So' and cv. 'Wai Chee' litchis at 5°C for 4 weeks, retaining the appearance and increasing disease control (Jacobi *et al.*, 1993). The success of the vapour heat treatment is cultivar dependent, which depends on the anatomical features of the pericarp such as thickness. In susceptible cultivars, such as 'Kwai May Pink', vapour heat treatment can cause a loss of membrane integrity, electrolyte leakage, PPO activation, pH fluctuation and

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pericarp browning (Wong *et al.*, 1991). Taiwanese litchi cultivars were reported to respond well to vapour heat treatment, suggesting that the cultivars were more heat tolerant (Jacobi *et al.*, 1993).

Litchi fruit subjected to hot water brushing treatment, followed by HCl and Prochloraz® (9N-propyl-N-[2-(2,4,6-trichlorophenoxy) ethyl] imidazole-1-carboxamide) dip treatments, maintained uniform red colour and excellent eating quality in terms of taste and flavour during storage for at least 35 days (Lichter *et al.*, 2000). Hot water brushing at 25°C for 20 s was observed to reduce or inhibit PPO activity in the pericarp by uniformly exposing the fruit to the acid by a brushing action. It was reported that the success of hot water brushing depends on fungicidal treatment. Although fungal growth was controlled at low temperatures, transfer of the fruit to market shelf temperature enhances colonisation by fungi. According to Lichter *et al.* (2000), hot water brushing does not provide antifungal protection of litchi fruit. The commercial application of hot water brushing remains a question until an alternative measure is found to replace the prochloraz dip to control decay on the market shelf. This is due to increasing concerns of health conscious consumers. Hot water spray is preferred over a hot water dip, although both methods are equally effective in retaining the red colour of the pericarp, but fungal rot is a major problem since hot water does not provide additional protection (Olesen *et al.*, 2004). Furthermore, *Penicillium* spp. were recovered from litchi fruit that were treated with hot water brushing and HCl (without prochloraz). It was concluded that dipping litchi fruit in HCl eliminates infections by common opportunistic fungi and selects the *Penicillium* species including *P. commune* (Lichter *et al.*, 2004). It is also reported that the *Penicillium* isolates on litchi do not belong to typical plant pathogenic species such as *P. italicum* or *P. expansum* (Lichter *et al.*, 2004). Fungal growth was inhibited on litchi fruit subjected to hot water brushing and thereafter dipped in omprazole and erythrosine B, the inhibitors of pH homeostasis. Their efficacy was observed to increase significantly at lower pH and in combination with weak acids such as sorbic acid and propionic acid (Zhang *et al.*, 2005).

However, a contradictory observation was reported by Hu *et al.* (2005) on heat treatments of litchi cv. 'Guiwei'. Heat treatments increased anthocyanase activity in the pericarp with rapid discolouration and a subsequent decline in anthocyanin content. Furthermore, hot water dip treatments at 50°C for 2 min, or at 55°C for 1 min, caused deleterious effects on pericarp colour, quality parameters and surface structure, e.g. flattening of the highly ornamented pericarp surface, homogeneous with occasionally lifted wax plates due to melting of the wax layer (Sivakumar and Korsten, 2006b).

15.7.4 Biocontrol agents

Due to the challenges associated with chemical disease control, postharvest decay control in litchi recently became more focused on the use of naturally occurring non-pathogenic bacteria or yeasts as antagonists. Application of antagonists to control postharvest diseases is more likely to be efficacious after harvest than in

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the field, because the storage environment around the fruit can be managed more easily to favour antagonist growth. The biocontrol agent *Bacillus subtilis* was found to be effective in controlling postharvest decay in litchi cvs. 'Madras' (Korsten *et al.*, 1993) and 'Huaizhi' (Jiang *et al.*, 2001), when kept at cold storage (5°C). The mode of action of this antagonist was reported as the antibiotic action of a cyclic polypeptide, iturin A (Jiang *et al.*, 2001; Gueldner *et al.*, 1998). The treatment with a cell-free suspension (extract) of the antagonist was effective in controlling fruit decay for a storage period of 30 days at 5°C (Jiang *et al.*, 2001). Although application of the antagonist did not alter the eating quality significantly, it caused moderate browning on the pericarp. The environment, therefore, still needs to be optimised to favour both antagonist survival and retention of fruit quality. More research is necessary on new biocontrol agents and their application as alternatives to chemical treatments in the litchi industry, in order to maintain a protective barrier, which does not allow fungal infection, without compromising fruit integrity.

15.7.5 Modified atmosphere storage

Modified atmosphere packaging (MAP) has the advantage of low cost and easy implementation at the commercial level (Flores *et al.*, 2004). The successful use of MAP depends on the specific permeation properties of polymer films to O_2 and CO_2 to generate atmospheres desirable for the postharvest life of horticultural commodities. MAP technology provides two advantages for litchi: it helps to reduce or prevent browning by maintaining a higher RH around the fruit inside the sealed plastic film, which prevents water loss due to transpiration, loss of membrane integrity, loss of electrolyte leakage and increased PPO activity. The control of postharvest decay could be achieved due to high CO_2 (>10%) composition.

Litchi fruit cv. 'Mauritius' subjected to hot water brushing treatment and followed by a 2 min HCl dip treatment (4%) amended with prochloraz and packed in laminated polyethylene bags (BoxiBag®, Atifon, Israel) with two types of perforations (micro and macro) showed higher CO_2, acetaldehyde and ethanol production in late harvested fruit than the early-season fruit in micro-perforated packaging at the end of storage (1.5°C for 4 weeks and 20°C for 3 days) (Pesis *et al.*, 2002). This further indicated that fruit maturity in terms of late or early harvest is a critical factor that determines the success of MAP technology. The anaerobic respiration resulted due to micro-perforation indicated the importance of selecting suitable films with specific permeability to create a desirable atmosphere around the fruit, in order to maintain superior overall quality. Different types of packaging (Xtend® or Bioriented Polypropylene, BOPP) or the same type of packaging (BOPP) with different perforations showed different gas compositions and RH around the litchi fruit, which affected their overall quality during long-term storage (Sivakumar and Korsten, 2006a). The BOPP-3 with 17% O_2, 6% CO_2 and ~90% RH around the early seasonal litchi fruit cv. 'Mauritius' reduced the rate of transpiration, and thereby prevented the browning related

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enzymatic mechanism, colour deterioration and weight loss, while retaining the overall fruit quality more than 21 days at 2°C and two days at 14°C (Schutte *et al.*, 1995). However, the MAP treatment showed lower L* value after 21 days cold storage and simulated market shelf condition for two days in cvs. 'Mauritius' and 'Mc Lean's Red'. Furthermore, the sensory panellists did not detect ethanol or acetaldehyde related off-flavours in these fruit. However, Tian *et al.*, (2005) reported ethanol production by fruit in MAP (15–19% O_2 + 2–4% CO_2) during low temperature storage in cv. 'Heiye'. South African cvs 'Mauritius' and 'McLean's Red' packed in bioriented polypropylene and held at 2°C for 95% RH showed similar patterns of CO_2 and O_2 levels within the packaging. The equilibrium modified atmosphere (steady state) was attained within the packaging after five days in cv. 'Mauritius' and three days in cv. 'McLean's Red'. The cv. 'Mauritius' showed slightly higher CO_2 concentration within the packaging (passive MAP) than cv. 'McLean's Red', indicating that 'Mauritius' has a higher rate of respiration than 'McLean's Red' (De Reuck *et al.*, 2009). When a mixture of 5% O_2 and 5% CO_2 was flushed into the punnets (active MAP) at the moment of packaging, replacing the initial atmosphere (air), the evolution of the internal atmosphere indicated that the flushing of gas mixture helped to minimise the time taken to reach the equilibrium state in both types of cultivars and it was established almost from the first day of storage (De Reuck *et al.*, 2009). When fruits were transferred from 2°C to 14°C, the CO_2 composition was observed to increase by ~2–2.3% in both types of packaging with ~1–1.5% decline in O_2 composition at the end of the second day at 14°C (Sivakumar *et al.*, 2008a).

These observations explain the higher permeability of the plastic films at low temperatures, preventing the build-up of CO_2 (Malakou and Nanos, 2005). The RH within the packaging was ~85% in BOPP-1 and 87% in BOPP-2 on the second day at 14°C. The observed changes in CO_2, O_2 and RH within the packaging at 2°C and 14°C were due to the effect of temperature in the storage environment on the film permeability. However, in MAP it is essential that the fruits are almost 100% browning and disease free since the pre-sorting of fruits before sale is not practicable in the large scale marketing chain. Therefore, there is a need to improve the application of MAP technology for litchi fruits in order to use it as a partial alternative to SO_2 fumigation, and the integrated treatments with MAP were researched intensively.

Hot water treatment and modified atmosphere packaging

Litchi fruit cv. 'McLean's Red' dipped in hot water at 55°C for 2 min, packed in Xtend® or BOPP, showed an increase in CO_2 composition around the fruit with a decrease in weight loss, fruit firmness and lower chroma with higher postharvest decay and browning during low temperature storage (Sivakumar and Korsten, 2006b). The loss of firmness was associated with water loss during hot water treatment. As stated by Wong *et al.* (1991), tolerance of high temperature depends on the cultivar and the morphological structure, especially the cuticular layer formation, pericarp thickness and the amount of wax deposits on the cuticle. The damage caused by hot water treatment on colour deterioration of the pericarp

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caused by PPO or POD activity cannot be compensated by the high RH or gas composition in the MAP.

Generally Regarded As Safe compounds and modified atmosphere packaging

Safe compounds such as ethylenediaminetetraacetic acid (EDTA), 4-hexylresorcinol or phosphoric acid were tested in combination with different types of BOPP (Sivakumar and Korsten 2006a). The EDTA and 4-hexylresorcinol inhibited the PPO that mediated browning but the effect on inhibition of browning and PPO was higher in BOPP-1 (Sivakumar *et al.*, 2008a). Furthermore, application of EDTA or 4-hexylresorcinol treatments with BOPP-2 and BOPP-1 showed reduction in yeast population on the fruit surface and showed antimicrobial properties (Sivakumar *et al.*, 2008a). However, the EDTA or 4-hexylresorcinol affected the hue value of the pericarp, which turned yellowish red during long-term low temperature storage. Dip treatments slightly altered the eating quality but no decay was reported (Sivakumar and Korsten, 2006a). A negative impact on fruit quality can be encountered when the fruit in MAP is subjected to temperature fluctuations during shipping, handling or at the retail display. Maintenance of an adequate temperature at 14°C on the marketing shelf is essential to retain the overall quality of litchi packed in MAP (Sivakumar and Korsten 2006a). The storage temperature varies among cultivars (Jiang *et al.*, 2003).

Biocontrol agent and modified atmosphere packaging

The biocontrol agent *B. subtilis* (registered as Avogreen® in South Africa) in combination with polypropylene packaging (PP) (14% O_2 and 5% CO_2) and stored at 2°C and at 95% RH and thereafter at market simulation at 14°C for 48 h retained the fruit quality of cv. 'McLean's Red' by reducing decay and decay associated browning during a simulated marketing chain of 20 days (Sivakumar *et al.*, 2007b). The mode of action of *B. subtilis* was reported as being due to the antibiotic action of a cyclic polypeptide, iturin A (Gueldner *et al.*, 1988; Jiang *et al.*, 2001).

Effective recovery of *B. subtilis* was observed in the *B. subtilis* + PP combination treatment and this combination treatment stabilised the natural ecological balance on the fruit surface (Sivakumar *et al.*, 2007b). The balance in the microbial population prevented the fungal decay in fruits subjected to *B. subtilis* + PP at the market-shelf, at 14°C. Combination treatment *B. subtilis* + PP increased the overall acceptability of the fruits by retaining the chroma and h° value of the pericarp at 2°C and at 14°C. The populations of *B. subtilis* remained at stable levels under modified atmosphere created by PP on the surface of litchi and maintained natural microbial balance on the fruit surface under cold storage (2°C) and in market-shelf conditions (14°C). The uneven structure of the pericarp segments with micro-cracks could have provided ideal sites for *B. subtilis* to colonise and multiply on the fruit surface. Therefore, it could be suggested that *B. subtilis* can act as a protectant during storage and transportation in combination with modified atmosphere packaging for marketing chains up to 20 days. The total marketability of fruit treated with a combination treatment of *B. subtilis* + PP

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was reported over 95% at 14°C, which suggests that this combination treatment is commercially viable. In MAP packaging it is essential that the fruits are almost 100% disease free since the pre-sorting of fruits before sale is not practicable in the large scale marketing chain. The presence of postharvest pathogens can act as inoculum and contaminate surrounding fruits in the packaging.

Chitosan and modified atmosphere packaging

The use of lower concentrations of chitosan would help to reduce the cost of production and would make application easier due to its lower viscosity. Pericarp browning was not observed in 'McLean's Red' in the chitosan and MAP treatment (De Reuck *et al.*, 2009). Although 'Mauritius' subjected to chitosan and MAP treatment showed pericarp browning (one to two spots), this treatment will not be beneficial for 'Mauritius' since the fruit sorting is not possible in MAP. The integrated treatment of chitosan with MAP showed a synergistic effect on inhibition of pericarp browning. The observed differences in severity of browning in 'Mauritius' and 'McLean's Red' in chitosan and MAP or stand-alone MAP revealed that the effectiveness of the treatment is cultivar dependent (De Reuck *et al.*, 2009). 'Mauritius' showed slightly higher CO_2 composition within the packaging than 'McLean's Red'. Chitosan (20 g L^{-1}) and MAP showed higher O_2 composition within the packaging than chitosan (1.0 g L^{-1}) and MAP and stand-alone MAP suggest reduced respiration in chitosan (20 g L^{-1}) + MAP packed fruit (De Reuck *et al.*, 2009). Chitosan coating on both cultivars has reduced the fruit respiration in MAP probably by modifying the endogenous CO_2 and O_2 levels due to its semi permeable filmogenic property. The filmogenic property of chitosan has been reported on litchi (Sivakumar *et al.*, 2005b). Both cultivars treated with chitosan and MAP showed higher a^* and b^* value after simulated market-shelf conditions. However, the effect of chitosan and MAP on retention of a^* and b^* value was higher in 'McLean's Red'. The effect of chitosan treatment in MAP on retention of red colour in the pericarp during storage depended on a^* value at harvest; therefore, the efficacy of chitosan treatment was higher in 'McLean's Red' since the a^* value was higher at harvest (De Reuck *et al.*, 2009). The chitosan and MAP integrated treatment showed a synergistic effect on anthocyanin content and colour retention. According to this study, in terms of retention of anthocyanin content and colour retention 'McLean's Red' is better suited to chitosan and MAP integrated treatment than 'Mauritius' (De Reuck *et al.*, 2009).

The integrated treatment, chitosan and MAP decreased the PPO and POD activity in both cultivars significantly more than stand-alone MAP. The inhibitory effect of chitosan and MAP treatment on the PPO and POD activity was higher in 'McLean's Red' than in 'Mauritius'. The integrity of membrane system was higher in 'McLean's Red' than in 'Mauritius' as shown by the higher leakage rate in 'Mauritius' in stand-alone MAP (De Reuck *et al.*, 2009). According to the observations on membrane integrity, it could be suggested that 'McLean's Red' has a more resistant cellular membrane system than 'Mauritius'. The chitosan application in MAP helped to reduce the leakage rate by preventing the loss of membrane integrity in 'McLean's Red'. A slight decline in SSC/TA ('Mauritius'

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57.4 and 'McLean's Red' 50.5) was observed in chitosan (1.0 g L^{-1}) and MAP in both cultivars after simulated market-shelf conditions when compared to freshly harvested fruit (De Reuck *et al.*, 2009). The chitosan and MAP helped to improve the quality retention of 'Mauritius' to an acceptable level of marketability. However, chitosan and MAP treatment can be applied to 'Mauritius' for domestic marketing chains that take 14–16 days (unpublished data). Cultivar dependent response for integrated treatment with chitosan and MAP was clearly stated in this study. Cultivar dependent response to chitosan treatment was reported by Ducamp-Collin *et al.* (2008) and 'Kwai May' was better suited to chitosan citric acid treatment than 'Wai Chee', showing that different cultivars responded differently to the chitosan dip treatment. Our observations demonstrated the potential of integrated use of chitosan and MAP as a commercial treatment to replace SO_2 fumigation during export for 'McLean's Red' (De Reuck *et al.*, 2009).

1-methylcyclopropene (1-MCP) and modified atmosphere packaging

The potential of using 1-MCP treatment in combination with MAP on quality retention of 'Mauritius' litchi was reported by Kruger *et al.* (2005). The application of 1-MCP at 1 mL L^{-1} reduced the browning and disease index in 'Huaizhi' stored at 28–33°C and 95–100% RH, for six days (Qu *et al.*, 2006). Both observations support the use of 1-MCP application on litchi quality retention during storage. Cultivars 'Mauritius' and 'McLean's Red' litchi fruit treated with 1-MCP at higher concentrations (500 or 1000 nL L^{-1}) in MAP (biorientated) polypropylene carrier bag (MAP; 35 μm thickness; size 40 cm × 18cm; O_2 permeance 38 × 10^{-14} mol s^{-1} m^{-2} Pa^{-1} at 23 °C according to manufacturer's instructions) (Sivakumar and Korsten, 2006a) revealed higher O_2 composition within the packaging (De Reuck *et al.*, 2009b). Although the pericarp browning index (BI) was observed to increase in fruit in the MAP treatment with higher 1-MCP concentrations in both cultivars after 21 days, 'Mauritius' showed higher pericarp BI than 'McLean's Red'. Increasing the concentration of 1-MCP to 500 and 1000 nL L^{-1} in MAP showed progressive decay incidence with severity when the storage life was extended to 30 days in 'Mauritius' (unpublished data). Furthermore, Qu *et al.*, (2006) reported inhibition of phenylalanine ammonia-lyase activity (PAL) in 'Huaizhi' with 1 mL L^{-1}, 1-MCP application. It was evident from the reports of Qu *et al.* (2006) that the disease index was low when the PAL enzyme activity was high. The cvs. 'Mauritius' and 'McLean's Red' subjected to combined treatments with 1-MCP (500 or 1000 nL L^{-1}) and MAP showed higher fruit firmness than the 300 nL L^{-1} 1-MCP and MAP treated fruit after 21 days' storage (De Reuck *et al.*, 2009a). The 1-MCP (300 nL L^{-1}) and MAP treatment retained the fruit firmness better than the SO_2 fumigated fruit (Sivakumar and Korsten, 2006a). In cvs. 'Mauritius' and 'McLean's Red', 1-MCP (500 or 1000 nL L^{-1}) treatments prevented the increase in SSC/TA after 21 days. The 1-MCP (500 and 1000 nL L^{-1}) delayed the respiration, resulting in a decline of SSC/TA by keeping the SSC unchanged. The SSC increased up to 19–20% and TA increased to 0.8–1% in SO_2 fumigated fruits, resulting in a lower SSC/TA ratio (Sivakumar and Korsten, 2006a) and the SSC/TA ratio determines the litchi taste and flavour. The litchi fruit subjected to 1-MCP

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(300 nL L^{-1}) and MAP treatment retained their good taste and flavour (unpublished data). The magnitude of 1-MCP on colour loss during storage depends on the a* value at harvest; therefore, the efficacy of 1-MCP at higher concentrations was lower in cv. 'McLean's Red' since the colour values were higher at harvest. The colour changes in both cultivars, with respect to a* and b* were reduced after 21 days with 1-MCP (300 nL L^{-1}) and MAP combined treatment (De Reuck *et al.*, 2009a).

The loss of anthocyanin content during low temperature storage was reduced by 1-MCP treatment at 300 nL L^{-1} in combination with MAP. However, a significant decrease in anthocyanin content was observed in both cultivars in the combined treatments with higher concentrations of 1-MCP (500 or 1000 nL L^{-1}) (De Reuck *et al.*, 2009a). The inhibitory effect of 1-MCP at 1000 nL L^{-1} was probably due to a lower PAL enzyme activity (Jiang *et al.*, 2001). PAL enzyme is a key enzyme in the biosynthesis of phenolics (Cheng and Breen, 1991). Furthermore, Qu *et al.* (2006) observed an increase in pericarp browning while the PAL enzyme activity declined in cv. 'Huaizhi' stored at 28–33°C. Therefore, the reduction in anthocyanin content in cvs. 'Mauritius' and 'McLean's Red' could be due to the reduction of PAL enzyme activity. The PPO activity in cv. 'Mauritius' was ~50 % higher than in 'McLean's Red' after 14 days' storage in 1-MCP (300 nL L^{-1}) and MAP treatment (De Reuck *et al.*, 2009a). The combined treatments with MAP and 1-MCP at 500 and 1000 nL L^{-1} 1-MCP showed higher PPO activity in fruit stored up to 14 and 21 days in both cultivars. The POD activity also showed similar trends as PPO in 1-MCP and MAP integrated treatments. Fruit in 1-MCP (300 nL L^{-1}) and MAP showed lower POD activity than fruit in other treatments (De Reuck *et al.*, 2009a).

The 1-MCP (300 nL L^{-1}) and MAP showed a lower pericarp relative leakage rate than other treatments. The effect of 1-MCP (300 nL L^{-1}) and MAP on membrane system integrity was higher in cv. 'McLean's Red' than in cv. 'Mauritius' (De Reuck *et al.*, 2009a). The relative leakage increased in the pericarp in combined treatments with increasing 1-MCP concentrations. The integrated 1-MCP treatments with 500 and 1000 nL L^{-1} 1-MCP showed a higher relative leakage than stand-alone MAP treatment in cv. 'Mauritius' after 14 days' storage. After 21 days' storage, 1000 nL L^{-1} 1-MCP revealed a higher relative leakage rate in both cultivars, and cv. 'Mauritius' showed a higher relative leakage rate than cv. 'McLean's Red' (De Reuck *et al.*, 2009a). Under long-term storage conditions, loss of membrane integrity was reported as a result of pericarp senescence (Duan *et al.*, 2004). The loss of cell membrane integrity is known as a result of malfunction of membrane lipid biosynthesis and membrane repair due to shortage of ATP, resulting in ion leakage and cellular decompartmentalisation (Qu *et al.*, 2006). Consequently, the browning reactions will take place when anthocyanins come into contact with the oxidising enzymes PPO and POD. Qu *et al.* (2006) reported that a stable energy charge is essential to maintain normal metabolism in harvested litchi fruit, the application of 1-MCP at 1 mL L^{-1} helped to minimise the change in energy charge during storage compared to untreated control fruit. Although there is uncertainty about the role of C_2H_4 in pericarp browning of harvested litchi

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(Pang *et al.*, 2001), the pericarp browning increased in C_2H_4 treated 'Huaizhi' during storage at 28–30°C for six days. Respiration in the pericarp also increased after a dip in ethephon (50g L^{-1}) in cv. 'Guiwei', but this increase was not observed in the aril and did not induce cyanide-insensitive respiration, one of the features of non-climacteric fruit. According to Qu et al. (2006), C_2H_4 treated fruit showed lower energy charge while the untreated control revealed higher energy charge. However, the 1-MCP treatment reduced change in energy charge and maintained the normal metabolism. The colour retention and absence of pericarp browning in 'McLean's Red' revealed that the 'McLean's Red' is better suited to 1-MCP and MAP combination treatment. However, we consider the use of non-uniform coloured fruits, late seasonal fruits, and the time delay between harvesting and packing operations to be the limiting factors for this treatment.

15.7.6 Controlled atmosphere storage

Litchi fruit cv. 'Huaizhi' stored at 1°C under controlled atmosphere (3–5% CO_2 and 3–5% O_2) at 90% RH showed good browning control, while retaining the fruit quality up to 30 days (Lin *et al.*, 1998). Duan *et al.* (2004) suggested that litchi cv. 'Huaizhi' stored in pure O_2 (100% O_2 and 0% CO_2) for six days at 28°C showed significantly reduced pericarp browning. It is evident from their investigations that the pure O_2 inhibited the activities of PPO and anthocyanase involved in the enzymatic browning mechanism. Therefore, pure O_2 atmosphere helps to prevent the degradation of anthocyanin by preventing hydrolysis of sugar moieties from anthocyanin to anthocyanidin and the degradation of anthocyanidin by PPO to brown polymers. Duan *et al.* (2004) reported the presence of high levels of anthocyanins in the litchi pericarp by the end of six days' storage. The application of pure O_2 maintained high total soluble solids and titratable acidity in the aril (Duan *et al.*, 2004). Application of high O_2 storage (70% O_2 + 0% CO_2) for one week followed by 5% O_2 + 5% CO_2 storage at 3°C and 95% RH for 14, 24 and 48 days showed significant reduction of decay, while browning increased after 14 days in cv. 'Heiye'. According to Tian *et al.* (2005), the anthocyanidin content in the pericarp was observed to decrease slowly when compared to the control and the ethanol content responsible for the off-flavours was reduced when the fruit were exposed to 70% O_2 for 1 week, followed by 5% O_2 +5% CO_2 at 5°C.

Tian *et al.* (2005) also indicated the beneficial effects of higher O_2 in controlled atmosphere storage to limit the PPO and POD activities, maintain higher anthocyanin levels, prevent decay and retain good fruit quality. Superatmosphere O_2 at 50% showed a significant effect on inhibition of browning in cv. 'Hong Huay' for eight days longer than the ambient temperature, but increased concentrations up to 70% did not show additional control of browning (Techavuthiporn *et al.*, 2006). However, the effect of pure or higher O_2 concentrations during long-term storage on retention of overall quality in terms of storage life and disease development requires further investigation. The CA storage is beneficial for large volume transport. Once the fruit is removed from the CA in a high RH environment

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and placed in commercial storage conditions, the risk of desiccation will increase. Therefore, it is recommended to pack the fruits in suitable modified atmosphere packaging at the destination in order to prevent desiccation associated pericarp browning after removal from CA storage.

15.8 Processing

15.8.1 Fresh-cut processing (or potential for fresh-cut processing)

Although the pericarp browning affects the marketability of litchi fruit, the arils of such fruit can be preserved by adopting minimal processing technologies to provide the consumers with 'fresh-like' fruit (aril) in a convenient manner. The adaptation of minimal processing technology in the litchi fruit industry will help to reduce the postharvest losses of fruit due to pericarp browning and decay.

Preservation of arils as a minimally processed product is beneficial for commercialisation and value addition. However, the shelf life of the minimally processed product (aril) quality is affected by discolouration (development of yellowish colour), loss of texture and mould growth. The shelf life of the minimally processed litchi can be extended up to 24 days when the arils are dipped in 502 g Kg^{-1} sucrose solution containing 4.9 g Kg^{-1} cysteine, 20 g kg^{-1} ascorbic acid, 0.134 g kg^{-1} 4-hexylresorcinol, 20 g kg^{-1} calcium lactate for 10 min at 570 mm Hg vacuum and packaging in polystyrene trays and wrapping with a polypropylene film (150 gauge) and sealing with a −355 mm Hg vacuum packaging machine. Furthermore, it was evident from the findings of Shah and Nath (2006) that the packing in moderate vacuum with osmo-vacuum dehydration was highly effective in preserving the product against microbial proliferation and chemical changes. The antibrowning treatments effectively controlled the browning and the colour changes during 24 days' storage. However, the authors concluded that future research must focus on improving the firmness of the arils with other treatments or different gas combinations (Shah and Nath, 2006).

15.8.2 Drying

Due to its highly perishable nature and seasonal fruit bearing pattern, the litchi fruit is subjected to processing. Further, the development of value-added products provides extra income and employment opportunities for the local producers and minimises the constraints associated with limited postharvest storage life and losses. In general, dried litchi is marketed in the form of flesh and dried whole fruit. Intact dried litchi is a popular commodity in the Chinese local market. The litchi drying process is becoming popular in Thailand where marketing is almost exclusively under the control of middlemen and processors. According to the studies conducted by the Agricultural Research Council–Institute for Tropical and Subtropical Crops (ARC-ITSC), cv. 'McLean's Red' was selected for processing rather than cv. 'Mauritius' (Kritzinger and Kruger, 2002). Among the other South African litchi cvs. 'Wai Chee' and 'Kwai May' showed most potential and cv.

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'Haak Yip' was inferior. Further according to the ARC-ITSC reports a drying temperature around 55°C for three weeks was selected as the most efficient drying regime (Kritzinger and Kruger, 2002). According to the observations fruit with a moisture content of 20–30% were found to have raisin like taste with a soft texture; on the other hand, fruit dried to 5–10% moisture content resembled dried dates in appearance with a toffee texture and taste (Kritzinger and Kruger, 2002). For drying the fruit has to be picked at best quality and thereafter it is subjected to different processing treatments such as washing in boiling water, fumigation with SO_2, dipping in HCl and washing in tap water (Janjai *et al.*, 2010). Generally oven drying under controlled temperature conditions is adopted. The moisture diffusivity of the flesh, seed and skin of litchi fruit are highly dependent on temperature (Janjai *et al.*, 2010). Also the sensory evaluation showed higher scores for appearance, colour, texture, flavour, taste and overall acceptance for litchi fruit dried at temperatures of 50–80°C. Osmotic dehydration was the most reported pre-treatment adopted prior to air drying and had received considerable attention due to low temperature and reduced energy requirements. On this basis the pre-treatment with glycerol and trehalose [Generally Regarded As Safe (GRAS) food additives by the US Food and Drug Administration (FDA)] revealed the best potential for browning retardation in litchi fruit during storage at 25°C and at 45–60% RH for 6 months (Mahayothee *et al.*, 2009).

15.8.3 Canning

The most common method of preserving litchi is canning. As with other fruit and vegetables canned, a pink colouration develops in canned litchi. This colouration affects the sensory quality, and also leads to nutrional losses. It is due to the oxidative reactions of PPO and POD in the damaged fruit tissues (Phunchaisri and Apichartsrangkoon, 2005). The POD is reported to have a relatively higher thermal stability. The optimal pH for litchi POD and PPO are 5.0–8.0 and 7.00 respectively. Addition of SO_2 to the syrup prevented the development of the pink colour in the end product (Zee *et al.*, 1998). The precursors of the pink coloured compounds belonged to the flavonoids. Phunchaisri and Apichartsrangkoon (2005) evaluated the possiblity of using high pressure as an alternative to canning and reported that the pressure treatment caused less loss of visual quality in both fresh and syrup processed litchi than thermal processing.

15.9 Conclusions

Research on postharvest physiology of litchi has progressed and the relationship between physiological browning and enzyme mediated browning has been established. All the technologies mentioned above are focused on maintaining overall fruit quality for 18–30 days. The available technologies can be used to replace SO_2 fumigation for marketing chains less than 22 days, especially for niche markets, where the fruit can be sold as organic produce. Due to increased

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production in litchi exporting countries, sea shipment was used as a convenient and economical mode of transportation to export destinations. The transport time, including the voyage time, cold storage and display at the retailer end has extended the postharvest chain to more than 30 days. However, the transport time has to be shortened to 21 days in order to retain overall fruit quality. It is also evident from the available literature that the quality retention after different postharvest treatments is cultivar dependent.

The type of litchi cultivar should be taken into consideration when testing and deciding on alternative postharvest treatments. Different litchi cultivars showed differences in pericarp structure formation, wax contents, mineral composition, physicochemical parameters and aroma components. The anthocyanin concentration was higher in cv. 'McLean's Red' than in cv. 'Mauritius'. Further, consumer acceptance is higher for cv. 'Mauritius' than for cv. 'McLean's Red' due to the differences in aroma compounds. Although no literature is currently available on the effect of SO_2 fumigation on aroma profiles of litchi fruit, research has shown that the aroma compounds are also affected by the SO_2 fumigation and postharvest treatments. In addition to evaluation of alternative treatments on overall quality, the effect on aroma profiles of the specific litchi cultivar needs investigation, as taste and aroma are important factors in determining consumer acceptance.

When considering litchi postharvest browning and decay control approaches, the available literature indicates intensive research on finding suitable alternatives to SO_2 fumigation. The alternative treatment has to be implemented in order to replace the currently used SO_2 fumigation especially to niche markets catering for health conscious consumers. MAP technology is beneficial and should easily gain commercial acceptance; therefore future research is needed to optimise the storage temperature and desired gas compositions in MAP which depends on the type of cultivar, growth conditions and season (early or late) and must therefore be cultivar specific. To replace fungicide treatments, protective packaging with high CO_2 in low temperature storage can result in off-flavour development in the aril; therefore a 3–5% CO_2 concentration is recommended for litchi (Kader, 1993). However, the MAP has to be integrated with postharvest treatments especially with chitosan in order to prevent postharvest decay during fluctuations of temperature or mismanagement of the cold chain. Furthermore, successful implementation of MAP technology and efficient cold chain management is vital. The use of lower concentrations of chitosan would be beneficial to reduce the cost of production and for easy application due to its lower viscosity. Therefore, MAP technology could be considered as a more convenient method for marketing litchi. The MAP application must be extended by using suitable bio-degradable consumer units.

The other option for large volume exports is to transport the fruits under controlled atmosphere conditions and after arrival to pack them in MAP in order to prevent desiccation and browning related mechanisms and cross contamination. However, as mentioned above, the gas composition for controlled atmosphere has to be optimised according to the different export cultivars. Furthermore, repacking the fruits in MAP will become a more laborious process in the marketing chain.

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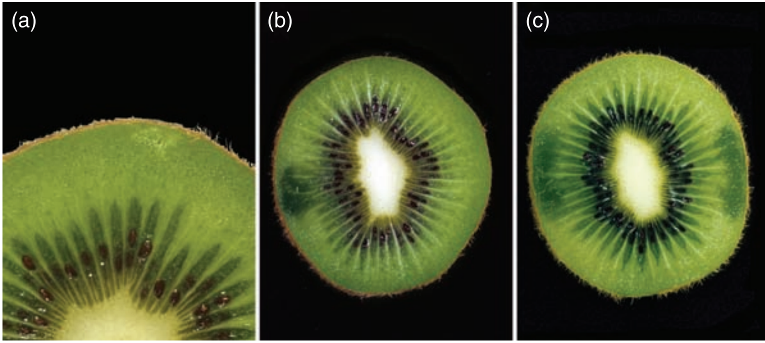

Plate XXV (Chapter 14) Impact (a and b) and compression (c) damage in 'Hayward' kiwifruit.

Plate XXVI (Chapter 15) Litchi fruit (cv. McLean's Red).

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Plate XXVII (Chapter 15) Litchi fruit after sulphur dioxide fumigation.

Plate XXVIII (Chapter 16) Fruit tree of longan cv. 'Shixia' grown in Guangdong province, China.

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16

Longan (*Dimocarpus longan* Lour.)

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Abstract: Mature longan (*Dimocarpus longan* Lour.) fruit have a succulent, edible and white aril. Maturity (ripeness) can be determined on the basis of fruit weight, skin colour, flesh sugar, acid concentration, sugar:acid ratio, flavour or days from anthesis. Longan fruit have a short shelf life at ambient temperature. Main determinants of shelf life and marketability are microbial decay and pericarp browning and postharvest protocols have been developed to reduce these defects. Recent research has focused on maintaining high fruit quality. Quarantine issues associated with fruit fly are also being addressed to secure overseas markets for longan fruit, and heat treatments and gamma or ionizing radiation disinfestation protocols have been investigated. In the light of health benefits, functional food products from longan fruit should be developed in the future.

Key words: *Dimocarpus longan*, longan, postharvest, quality, processing.

16.1 Introduction

Longan (*Dimocarpus longan* Lour.) is a subtropical evergreen tree belonging to the family *Sapindaceae* (Huang, 1985; Tindall, 1994). It is grown commercially in many countries, including China and Thailand, which account for most of the fruits' production (Anupunt and Sukhvibul, 2005; Nicholls, 2001; Poerwanto, 2001; Subhadrabandhu and Yapwattanaphun, 2001). China is still the country of greatest longan production (Huang *et al.*, 2005). Production of longan fruit has increased over recent decades because of improvements in agronomic practices and other aspects of crop management (Wong, 2001; Jiang *et al.*, 2002). Increasing production of longan fruit raises prospects for novel and improved postharvest treatments and handling protocols, including expanded processing, for this crop.

Longan fruit has a thin, leathery and indehiscent pericarp surrounding a succulent edible aril (see Plates XXVIII and XXIX in the colour section between

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pages 274 and 275). The aril contains a large dark brown seed. The fruit is prized on world markets for its flavoursome semi-translucent to white aril (Jiang *et al.*, 2002; Li *et al.*, 2004). Longan fruit mature and ripen in the hot season, and have a short shelf life at ambient temperature (Lin *et al.*, 2002b; Guo *et al.*, 2005). Major disorders affecting longan fruit appearance are pericarp browning and pathological decay (Jiang *et al.*, 2002; Shi *et al.*, 2008). Accordingly, most postharvest research has focused on reducing these two disorders to maintain high fruit quality (Jiang *et al.*, 2002; Lin *et al.*, 1997). Research on postharvest biology and technology for longan fruit has advanced at a rapid pace. This chapter considers the current status of postharvest research, particularly that since 2002 (Jiang *et al.*, 2002) with an emphasis on postharvest handling systems.

16.2 Postharvest characteristics

16.2.1 Maturity

Longan fruit are non-climacteric and, therefore, do not ripen until they are harvested (Paull and Chen, 1987). Consequently, the fruit must be picked at optimal eating quality. General guidelines for harvesting are difficult to prescribe because of the wide range of cultivars and production conditions (Pan *et al.*, 1996). In practice, longan maturity (ripeness) is usually based on fruit colour and flavour (Lin *et al.*, 2003). Although skin colour is the most commonly used harvest index, the relationship between maturity and colour varies with cultivar, environment and cultural practices. Sugar and acid composition of longan fruit aril have shown promise as a basis for commercial maturity standards. Titratable acidity (TA) and the ratio of total soluble solids (TSS) to TA are good indicators of flavour. In China, TA and TTS are now generally considered the most reliable indicators of taste for most longan cultivars. Han *et al.* (2008) investigated maturity standards for 'Shixia' longan fruit and determined that optimal harvest was 90–95 days after fruit set. Nonetheless and in practice, longan fruit are still harvested on the basis of their colour and flavour (Lin *et al.*, 2002b).

16.2.2 Composition

Longan is both a tasty and a nutritional subtropical fruit. Since ancient times, longan fruit pericarp has been used as a traditional Chinese medicine for enhancement of human immunity (Zhao *et al.*, 2007). Table 16.1 presents the principal nutritional components of longan fruit aril tissue (Li *et al.*, 2004; Wall, 2008).

The concentration of total sugars increases in longan fruit aril during ripening, with absolute sugar content varying with stage of maturity and cultivar (Han *et al.*, 2008; Lin *et al.*, 2003). The major sugars are sucrose, fructose and glucose. Li *et al.* (2009) reported a decreasing trend in sugar content of longan fruit juice during storage.

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Table 16.1 Nutritional composition per 100 g of longan fruit aril

Moisture (%)	81.4
Total carbohydrate	12.38–22.55
Carotene (μg.100^{-1} g)	20
Vitamin K (mg.100^{-1} g)	196.5
Reducing sugar (%)	3.85–10.16
Retinol (μg.100^{-1} g)	3
Protein (g.100^{-1} g)	1.2
Riboflavin (mg.100^{-1} g)	0.14
Fibre (g.100^{-1} g)	0.4
Ascorbic acid (mg.100^{-1} g)	43.12–163.7
Fat (%)	0.1
Nicotinic acid (mg.100^{-1} g)	1.3
Ash (g.100^{-1} g)	0.7
Thiamine (mg.100^{-1} g)	0.01

Longan flesh contains malic and tartaric acids (Li *et al.*, 2004). Other organic acids, including oxalic, citric and succinic acids, have also been identified. Malic acid and citric acid are highest at the intermediate maturity stage, and gradually decrease thereafter. The organic acid concentration in longan fruit typically increases until the 3/4 ripe stage, and then declines in ripe fruit (Y. M. Jiang, unpublished data).

About 28 volatile compounds from fresh longan aril have been identified to date. The major volatiles include β-ocimene, 3,4-dimethyl-2,4,6-octatriene, ethyl acetate, allo-ocimene and 1-ethyl-6-ethylidene-cyclohexene (Zhang *et al.*, 2008; 2009; Zhang and Li, 2007). Two volatile compounds in the aril, allo-ocimene and 3,4-dimethyl-2,4,6-octatriene, decrease during storage (Zhang *et al.*, 2008). Different volatile profile characteristics for longan fruit may occur across cultivars, environments and cultural practices.

Lysophosphatidyl choline, phosphatidyl choline, phosphatidyl inositol, phosphatidyl serine, phosphatidyl ethanolamine, phosphatidate and phosphatidic acid glycerol have been detected in longan aril tissue (Li *et al.*, 1995). Such phospholipids can be metabolized by a variety of membrane lipid-related enzymes and purportedly enhance immune function in human consumers. Thus, longan fruit flesh may have beneficial effects on human health.

16.2.3 Texture

There has been little investigation of changes in the longan aril texture before and after harvest. Aril breakdown or softening often occurs in longan fruit that had sound pericarp during storage. Deterioration starts near the pericarp, particularly adjacent to the pedicel, and involves loss of turgidity, translucency and flavour (Su *et al.*, 2006; Su and Yang, 1996). The severity of this problem varies among cultivars. A recent study indicates that expansin and xyloglucan

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endotransglycosylase genes are differentially expressed (Zhong *et al.*, 2008). Also, expression of endo-1,4-β-glucanase gene increases during aril breakdown in harvested longan fruit (Xiao *et al.*, 2009). Lin *et al.* (2007a) proposed that the early and middle phases of the aril breakdown development were attributable mainly to actions of pectinesterase, polygalacturonase and cellulase, whereas β-galactosidase plays a key role in the late phase.

16.2.4 Respiration

As noted above, longan fruit are non-climacteric. Xu *et al.* (2009) and Zhao *et al.* (2005) found a continuous decline in respiration rate during longan fruit ripening. Similarly, fruit stored at 4°C showed a progressive decline in respiration (Zhou *et al.*, 1997a). However, a rapid post-storage increase in respiration rate of longan fruit at ambient temperature was apparently associated with disease development (Y. M. Jiang, unpublished data).

16.2.5 Ethylene evolution

Longan fruit produce relatively low levels of ethylene after harvest compared with climacteric fruits. However, high ethylene production rates by longan fruit at ambient temperature have been correlated with fungal infection (Y. M. Jiang, unpublished data). Moderate to high ethylene production rates have also been reported coincident with skin desiccation or storage at high temperatures of 28–32°C (Y. M. Jiang, unpublished data). The ethylene production rate of fruit stored at 1–3°C remained relatively constant for about 30 days after first production (Jiang and Li, 2001).

16.2.6 Peroxidative activity

Activity of superoxide dismutase as an important enzyme of the antioxidant system in longan fruit pericarp decreases while concentrations of malondialdehyde, a product of peroxidated membrane lipids, increase along with membrane breakdown during storage of longan fruit at ambient temperature (Chen *et al.*, 2009; Lin *et al.*, 2005). Also, the antioxidant capacity of the pericarp decreases during storage (Duan *et al.*, 2005b). Thus, the decreased antioxidant ability of the pericarp of harvested longan fruit to eliminate active oxygen species enhances peroxidation of membrane lipids. Consequently, the non-climacteric fruit senesce and further deteriorate through microbial attack.

16.2.7 Ultrastructural changes

Gradual breakdown of cellular ultrastructure in longan fruit has been recorded at ambient temperature. Qu *et al.* (2001) found that membrane breakdown commenced in the mesocarp tissue of the pericarp within 2 days of harvest, and in exocarp sclerenchyma cells after 5 days. Differences in storability among 'Shixia', 'Chuliang' and 'Tuzhong' were correlated with their pericarp structure.

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Enhanced storability was associated with a continuous thick cork layer, groups of stone cells in close arrangement, a well developed vasculature and a thick cuticle (Qu *et al.*, 2001; Lin *et al.*, 2002). Microstructure may also modulate disease incidence in terms of relative resistance of the fruit to invasion by pathogens.

16.2.8 Pathology

Longan fruit are highly susceptible to postharvest decay by both bacterial and fungal pathogens. Important disease causing organisms include *Botryodiplodia* sp. and *Geotrichum candidum* (Jiang *et al.*, 2002). Around 106 species of microorganisms have been isolated from longan fruit, this total being comprised of 36 bacteria, 63 fungi and seven yeast species. Fruit infection by organisms, such as *Botryodiplodia*, may occur either in the field or through the cut stem end during harvesting or handling (Chen *et al.*, 1999; Lin *et al.*, 2006).

16.3 Postharvest handling

16.3.1 Sorting and grading

Sorting and grading of longan fruit after harvest should be conducted in a shaded and well ventilated area, or in a packinghouse with low temperature control. Sorting is undertaken as a manual process to eliminate undersized, immature, overripe, split pericarp and/or pathogen affected fruit (Lin *et al.*, 2002b). To ensure top quality fruit for a high price and quality aspirations for both domestic and foreign markets, longan fruit should be graded. However, no single international grading standard has been set for longan fruit. General criteria for quality are large and well coloured fruit, with sweet flesh. In China, fruit are divided into three grades according to the National Grading Standard for fresh longan fruit (GB12049289). In Thailand, fruit counts in the range of 50–75 fruit.kg^{-1} are considered top grade. Fruit for export must fall within the Grade LX limit of ≤60 fruit.kg^{-1}. Fruit of Grade A (60–70 fruit.kg^{-1}), Grade AB (70–80 fruit.kg^{-1}) and lower grade (≥80 fruit.kg^{-1}) are often used to produce canned and dried products. Longan grades for export to various specific markets may differ, and fruit exported to Canada, Singapore and Hong Kong should be Grades LX or A. Importantly, besides fruit size or fruit weight, consumers need to be satisfied with freshness, stalk length and skin appearance.

16.3.2 Precooling

Because longan fruit mature in the hot season, precooling is desirable to rapidly remove ‘field’ and ‘respiration’ heat loads. Various methods, including room cooling, forced-air cooling, hydrocooling, package icing and vacuum cooling, have been used for precooling longan fruit (Table 16.2). Room cooling may not

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Table 16.2 Recommendations for precooling of longan fruit

Cooling method	Handling protocol
Hydrocooling	Immersed in ice water for 1–3 h
Forced air cooling	Placed in cold house for 12–24 h
Vacuum cooling	Placed in vacuum cooler for 15–60 min

efficiently decrease temperature. Forced-air cooling is preferable, being much faster. When longan fruit are packed in plastic bags or fibreboard cartons, the cooling time should be extended. Application of ice water is a very fast cooling method currently used widely for longan fruit in China (Lin *et al.*, 2002b). Vacuum cooling is the most rapid method, and the surface temperature of longan fruit can be decreased from 28 to 7°C after just 11 min (Chen and Lin, 2000). Application of water to wet fruit prior to vacuum cooling can reduce weight loss and increase the cooling rate (Lin *et al.*, 2002b). However, vacuum cooling is not yet used commercially because of the high cost of vacuum coolers. Container venting and stacking should be optimized to suit any chosen method of fast cooling. In China, packaging of longan fruit with ice is widely practised for short distance transport over 1–3 days at ambient temperatures.

16.3.3 Fungicides

Fungicides are widely used commercially on longan fruit after harvest to inhibit pathogen development and extend storage life (Table 16.3). Major fungicides include thiabendazole, imazalil, thiophanate, sodium benzoate, NaClO, iprodione and sulphur (Jiang *et al.*, 2002; Lin *et al.*, 2002b), and most provide good control of postharvest pathogens on longan fruit. Treatment with 0.05% thiabendazole in combination with 0.05% iprodione exhibited more effective control of decay than did thiabendazole alone (Y. M. Jiang, unpublished data).

Among the fungicides, SO_2 fumigation has been widely used commercially as the most effective and practical postharvest treatment for control of decay and also colour change on longan fruit (Cai, 1988; Han *et al.*, 1999; 2001; Wu *et al.*, 1999). SO_2 fumigation can be achieved by burning sulphur powder at ambient temperature for 20–30 min with no humidity control, although recommendations vary slightly.

Table 16.3 Recommendations for fungicide treatment of longan fruit

Fungicide	Treatment protocol
SO_2	Burning sulphur powder at ambient temperature for 20–30 min.
Thiabendazole, iprodione or prochloraz	Dipped in 0.1% fungicide solution for 1–3 min.

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Alternatively, SO_2 liquid held in a pressurized cylinder can be vaporizing or sulphite compounds, such as sodium metabisulphate, can be dissociated. Liquid SO_2 and sulphite compounds have more advantages than burning sulphur powder but exporters still prefer to use the latter because of the convenient application. The most appropriate sulphur treatment for longan fruit when the transportation period is <2 weeks to importing countries is high concentration, short duration fumigation. Adoption of fumigation also depends on the scale of operation, marketing system and socioeconomic circumstances (Lin *et al.*, 2001; 2002b).

The dose of SO_2 in a fumigation chamber depends largely on sorption by the mass of fruit, free space in the room, and sorption by containers and other packaging materials (Li *et al.*, 1999). Also, the fruit stalk absorbs more SO_2 than does the flesh. The dose quantity of SO_2 is based mainly on the combination of the space and product mass. The mass of SO_2 required can be calculated (Lin *et al.*, 2002b): weight of $SO_2 = (A \times B \times C) + (D \times E)$; where: A is the concentration of SO_2 to be achieved (%); B is the free space in the room (L); C is weight of SO_2 per litre at 30°C (2.6 $g.L^{-1}$); D is mass of fruit (kg); and E is SO_2 sorption rate of fruit (gkg^{-1}). The mass (g) of sulphur (S) to be burned is the weight of $SO_2/2$. SO_2 fumigation for a minimum of 20 min should be timed once the S is completely volatilized. The SO_2 residue present in longan fruit was found to range from 1200–3200 $mg.kg^{-1}$ immediately after fumigation, and then declined by 50% over the first 2 days (Pan *et al.*, 1999). Applied S was largely located in the pericarp portion, while the aril exhibited only trace levels to a maximum <10–30 $mg.kg^{-1}$ (Ji *et al.*, 1999). After fumigation, SO_2 should be removed by aeration to safeguard human health and prevent environmental pollution. Also, the risk of SO_2 injury to longan fruit should be taken into consideration, this being dependent on application rate and duration. The damaged longan fruit are initially irregularly brown and then become transparent under the pericarp after 2 days from fumigation. Fumigation damage is also associated with an aril colour change from translucent to dull white (Han *et al.*, 2001; Pan *et al.*, 1999).

In recent years, there has been increasing concern about sulphur residues present in longan fruit, particularly as some people are highly sensitive to sulphites. Europe, Australia and Japan have set a maximum sulphur residue limit of 10 $mg.kg^{-1}$. In the US, sulphur is registered only for postharvest use on grapes. Alternative means of longan fruit decay and colour management, such as application of nitric oxide, chitosan and/or microbial antagonists, are needed for the future (Jiang, 1997).

16.3.4 Other handling technologies

Various alternatives to sulphur have been investigated to reduce postharvest fruit browning and rotting during storage and transportation. Duan *et al.* (2007a; b) reported that nitric oxide treatment inhibited lipid peroxidation and delayed skin browning of harvested longan fruit during storage. Application of ozone to harvested longan fruit markedly extended their shelf life (Whangchai *et al.*, 2005). Combination of ozone with organic acids helped further suppress postharvest

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decay and pericarp browning of harvested longan fruit (Whangchai *et al.*, 2006). Skin coatings are generally effective in extending storage life for harvested longan fruit, and two different waxes reduced water loss from 'Tongbi' fruit over 2 days at ambient temperature (Shi, 1996). Jiang and Li (2001) established that application of 2% chitosan extended storage life of 'Shixia' fruit at 5°C from 30 to 40 days. Dipping in acidic chitosan solution inhibited PPO activity, which helped delay pericarp browning. Jiang (1997) found that treatment with culture supernatant of *B. subtilis* was effective in controlling *Botryodiplodia* sp., and treated longan fruit stored for ~30 days at 5 °C with good turnout quality.

16.3.5 Handling system

Increasing production of highly perishable longan fruit in recent years has raised expectations of postharvest handling systems (Yang *et al.*, 2009). The system typically includes fungicide treatment, packaging, storage, transport and distribution, each of which can greatly influence fruit quality (Chen *et al.*, 1999; Holt *et al.*, 1983; Tongdee and Subhadrabandhu, 1992). Sorting and grading, precooling and fungicide treatment for longan fruit are commercial essentials (Chen *et al.*, 1998; Lin *et al.*, 2002b). However, precooling, fungicide treatment, packaging, storage, transport and distribution require enhancement in terms of integration and optimization to facilitate marketing of increasing longan fruit supplies. International grade standards and appropriate postharvest handling and cold chain protocols need to be established and applied. Also, to secure overseas markets for longan fruit, fruit fly quarantine issues need to be resolved. In this context, appropriate effective disinfestation protocols, such as might be offered by heat treatments and gamma or ionizing radiation, need to be optimized and accepted by the authorities (Follett and Sanxter, 2001; 2002; Hallman, 1999; McGuire, 1998). Future refinement of postharvest handling systems for longan fruit should also include consideration of preharvest management and handling influences on postharvest quality.

16.4 Packaging

In Asia at present, bamboo baskets are widely used as packaging for local markets of longan fruit. However, bamboo baskets are easily crushed out of shape, and attendant mechanical damage to longan fruit often occurs during storage and transportation. Alternative means of packaging, such as plastic crates and fibreboard cartons or boxes, are increasingly used (Lin *et al.*, 2001). Storage in plastic film bags has been effective in reducing moisture loss from longan fruit and, thereby, extending storage or shelf life (Lin *et al.*, 2001; 2002a; 2007b). Furthermore, You *et al.* (2004) reported that vacuum packaging can maintain longan fruit quality well. In Thailand and Australia, package and packing container standards are prescribed. For example, longan fruit for local and export markets are packed at 25 and 11 kg per plastic crate, respectively.

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16.5 Storage

Postharvest storage for longan fruit encompasses basic temperature management, and also application of modified atmosphere (MA) or controlled atmosphere (CA) systems.

16.5.1 Ambient temperature

Storage under ambient temperature conditions is heavily reliant upon application of fungicides (Chen *et al.*, 1988). Fungicide treatment in combination with plastic films can more effectively delay longan fruit browning and decay (Hong *et al.*, 1984). At best, longan fruit may store well for 6–9 days at ambient temperature (Su and Yang, 1996). In commercial practice, storage technology for longan fruit at ambient temperatures needs to be further improved.

16.5.2 Low temperature

Low temperature effectively retards pericarp browning, inhibits polyphenol oxidase activity (browning-related enzyme), represses pathogen development and reduces metabolism of nutritional constituents, thus prolonging longan fruit storage life (Lin *et al.*, 2001). In practice, application of fungicides followed by storage at 2–5°C gives a satisfactory storage life of about 30 days for longan fruit (Lin *et al.*, 2001). Although longan fruit store well for about 30 days at low temperatures, poststorage shelf life under ambient conditions is very short. This represents a major problem for marketing stored fruit. Longan fruit may suffer chilling injury when stored at low temperature (Zhou *et al.*, 1997), and optimum temperatures may vary with cultivars and production areas (Table 16.4). This pre- and postharvest interaction of genotypic and phenotypic variables demands further investigation. A storage technology using temperature fluctuation to reduce chilling injury has been proposed for longan fruit (Duan, 2006) but needs to be investigated. Guo *et al.* (2003) reported that the upper temperatures for ice crystal formation in longan fruit range from −2 to −14°C while the freezing temperature is below −40°C.

16.5.3 Modified and controlled atmospheres

Modified atmosphere (MA) and modified atmosphere packaging (MAP) are used commercially for harvested longan fruit. Packaging in plastic bags or sealed

Table 16.4 Storage temperature recommendations for selected major longan cultivars in China

Cultivar	Optimal storage temperature (°C)	Maximum postharvest life (days)
Shixia	1–2	40
Tongpi	1–3	35
Wulongling	3–5	30
Wuyuan	3–5	30

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containers can effectively reduce the rate of longan pericarp colour change (Lin *et al.*, 2005; Zhang *et al.*, 1997). For fungicide treated 'Shixia' fruit under MAP of 50% air + 50% N_2, Liang *et al.* (1998) recorded 92.3% sound fruit after 7 days at 25°C. However, as many longan fruit MA and MAP studies have lacked appropriate controls, further study is needed to confirm and optimize established beneficial effects.

CA storage is generally more effective in extending the storage life of longan fruit as compared with MA storage (Cheng *et al.*, 2009). Storage under 3% O_2 + 5% CO_2 has been effective in delaying pericarp browning and maintaining high TSS and ascorbic acid levels in 'Shixia' fruit aril (Jiang, 1999). Use of high CO_2 (15%) reduced fruit decay and extended storage life of longan fruit (Tian *et al.*, 2002). Su *et al.* (2005) reported that application of pure O_2 effectively inhibited the rate of longan fruit skin browning. However, use of either high concentration CO_2 or pure oxygen for longan fruit storage has not yet been applied in commercial situations.

16.6 Transport

16.6.1 Local market

Most fresh longan fruit are transported by truck to local distribution centres or wholesale markets (Lin *et al.*, 2002b; Shi, 1996) (Table 16.5). In China, local markets or distribution centres are typically ~20 km from production areas. For longan fruit transported by non-refrigerated truck, it is necessary to sell the harvested fruit quickly. Most longan fruit sent to distant markets (e.g. north China) are either transported by refrigerated trucks or packaged with ice and transported by non-refrigerated trucks.

16.6.2 Export market

Longan fruit are exported widely to overseas markets by land, sea or air (Table 16.5). Fruit from northern production areas in Thailand are taken to Malaysia and Singapore by refrigerated trucks. In recent years, most longan fruit shipment to overseas markets has been by sea because of lower cost and higher load capacity (Lin *et al.*, 2002b). Longan fruit can be loaded into 20- or 40-foot refrigerated

Table 16.5 Recommendations for transport and marketing of longan fruit

Method	Handling protocol
Local	Fungicide treatment, followed by packaging and non-refrigerated transport.
Export	Fungicide treatment, followed by packaging in plastic or fibre crate, and land, sea or air transport.

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containers for sea transport. However, longan fruit from Thailand are exported to distant markets by air.

16.7 Marketing

Marketing channels for longan fruit are well established. For Thai production, the proportions of fresh longan fruit for local market, export market and processed products are ~30, 30 and 40%, respectively. Canned and dried longan products are exported. In China, longan fruit is mostly marketed locally (Jiang *et al.*, 2002). Exports of longan fruit from Thailand and Vietnam are increasing rapidly, with Thailand currently being the biggest exporter, followed by Vietnam.

16.8 Processing

Dried longan fruit, referred to as 'nuts', are popular in Asia. They are often dried outdoors. However, the resulting nuts can vary greatly in quality (Nagle *et al.*, 2008; Tippayawong *et al.*, 2009). Electric oven drying at a controlled temperature is used commercially (Chang *et al.*, 1998). In recent years, other drying technologies, such as two stage superheated steam and hot air (Somjai *et al.*, 2009) and forced convection and hot air recirculation (Tippayawong *et al.*, 2009) supported by neural network modelling (Janjai *et al.*, 2009), have been investigated and developed for longan fruit. Moreover, longan fruit can be frozen (without adverse effects on the aril), canned in syrup or processed to produce juice or wine. Due to their high TSS content, little sugar additive is required and longan fruit can even be canned in their own juice. Canned longan fruit tend to retain their characteristic flavour. Increasing production of longan fruit with their relatively short postharvest life as a fresh commodity has raised expectations of greater processing opportunities for this crop. As is the case these days with many other fruits, new and improved food products, including functional foods, are a clear research and development imperative for longan.

16.9 Conclusions

Decay and deterioration of visual appearance are the major postharvest problems of longan fruit. Although SO_2 fumigation has been used commercially to control pericarp browning and fruit decay, it leaves undesirable residues, alters the fruit taste and results in health hazards for consumers and packhouse workers. Thus, new attempts should be made to develop an alternative postharvest technology to maintain overall fruit quality of longan during storage, transportation and distribution.

There are barriers to the exportation of longan fruit because of quarantine issues associated with some species of fruit fly. Appropriate disinfestation protocols need to be developed urgently in these markets. The future development

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of postharvest technology is likely to focus on disease and browning control and quality maintenance of longan fruit.

The prospect of increasing production of longan fruit and its relatively short postharvest life as a fresh commodity raises expectations for increased processing opportunities for this crop. Although most of the fresh longan fruit are dried as nuts, longan-related foods are produced in China and Thailand. In the light of health benefits, functional food products from longan fruit should be developed in the future.

16.10 Acknowledgements

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Plate XXVII (Chapter 15) Litchi fruit after sulphur dioxide fumigation.

Plate XXVIII (Chapter 16) Fruit tree of longan cv. 'Shixia' grown in Guangdong province, China.

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Plate XXIX (Chapter 16) Arils of longan cv. 'Shixia' grown in Guangdong province, China.

Plate XXX (Chapter 17) Loquat fruits (*Eriobotrya japonica* Lindl.) of different varieties: (a) 'Jinwuxing'; (b) 'Jiefangzhong'; (c) 'Zaozhong 6'; (d) 'Dahongpao'.

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17

Loquat (*Eriobotrya japonica* L.)

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Abstract: Loquat (*Eriobotrya japonica* L), as a subtropical evergreen fruit tree, has been cultivated for over 2000 years, and is commercially cultivated in more than 20 countries. Loquat has a high market value and is considered a functional fruit because of special nutrient compounds such as phenylacetaldehyde, hexanal, (E)-2-hexenal, hexanoic acid and β-ionone. The fruit is perishable, easily damaged and loses commercial quality after harvest. In this chapter, we mainly introduce the general characteristics, quality characteristics, physiological disorders and decay of loquat fruit, as well as some postharvest treatments and storage technologies.

Key words: *Eriobotrya japonica*, loquat, quality characteristics, physiological disorders, postharvest technology.

17.1 Introduction

17.1.1 Overview

Loquat (*Eriobotrya japonica* Lindl) is a subtropical evergreen fruit tree, belonging to the family Rosaceae, subfamily Maloideae. The fruit tree originates in the cooler hill regions of southwestern China and is very well adapted to temperate areas (Lin *et al.*, 1999). Loquat cultivation dates back more than 2000 years, since the Chinese Han dynasty (100 bc). Loquat was introduced to Japan from China in ancient times, and then spread to other countries (Zhang *et al.*, 1990). Loquat fruits usually ripen in early summer in a hot and rainy climate, and the ripe fruits are spherical or oval in shape, orange or yellow in color (see Plate XXX in the color section between pages 274 and 275), and have soft and juicy flesh with a thin tough skin. Therefore, the fruits are not suitable for storage and transportation and have a relatively short postharvest life.

17.1.2 Worldwide importance and economic value

Loquat fruit has rich nutritional and commercial importance in terms of its special functional composition and consumer demand. Currently loquat is widely and

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commercially cultivated in more than 20 countries, including China, Japan, India, Australia, Brazil, Israel, Italy, Spain, Turkey and the US. China is the leading producer of loquat with more than 100 000 ha cultivating area and 380 000 tons annual production (Tian *et al.*, 2007). Loquat is a summer-harvested small fruit, and regarded as a functional fruit because of its special nutritional content. Consumers highly favor loquat fruit because of its mild, subacid and sweet taste, as well as an attractive flavor. Therefore, loquat fruit generally has a higher market value than other summer-harvested fruits such as peach, plum and apricot. However, loquat fruits are very perishable and susceptible to mechanical injury, physiological disorders and microbial diseases after harvest, so that the fruit can easily lose its flavor and can survive for only a short storage time. In general, it is estimated that about 20–30% of fresh loquat fruit produced in China are lost after harvest due to decay and quality deterioration, causing a serious economic loss (Tian *et al.*, 2007). Therefore, it is important to study the postharvest physiology and pathology of loquat fruit in order to integrate effective treatments and storage technology, which can be beneficial for controlling decay, maintaining quality and extending shelf life.

17.1.3 Culinary uses of fresh and processed fruit, nutritional value and health benefits

Ripe fruit contains nearly all the essential nutrients, including proteins, minerals and carotenoids. The major nutrient compounds of loquat fruit are shown in Table 17.1. Loquat fruit are commonly processed into different products in China, such

Table 17.1 Nutrient compounds of loquat fruit (per 100 g of fruit)

Constituent	Approximate value
Water content	86.73 g
Calories	47 kcal
Protein	0.43 g
Fat	0.20 g
Ash	0.50 g
Cholesterol	0 mg
Carbohydrate	12.14 g
Fiber (Total dietary)	1.7 g
Calcium	16 mg
Iron	0.28 mg
Magnesium	13 mg
Phosphorus	27 mg
Potassium	266 mg
Sodium	1 mg
Vitamin C	1.0 mg
Vitamin A	1528 IU

Source: USDA National Nutrient Database for Standard Reference, Release 22 (2009). For detail, see website: http://www.nal.usda.gov/fnic/foodcomp/cgi-bin/list_nut_edit.pl

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as juice, wine, jam, ointment and tea (see Plate XXXI). The processed fruit provides a variety of loquat products, more easily transported to consumers throughout the world than the fresh fruit, and processing also prolongs shelf life.

17.2 Maturity and quality

17.2.1 Maturity characteristics

Loquat fruit color is an important parameter for harvest, varying with cultivars from pale yellow to deep orange during ripening. The fruit is about 30–80 g, oval, rounded or pear-shaped depending on the cultivar, and there are 1 to 5 seeds (pips) grouped at the center of the fruit. About 60–80% of the fruit is edible. The flesh of ripe fruit is soft and juicy, and is white, yellow or orange. According to the flesh color, loquat can be sorted into two groups: white-fleshed and red-fleshed. The firmness of loquat fruit decreases to a low level with ripening, so the fruit is especially susceptible to mechanical injury.

17.2.2 Quality characteristics

Soluble solids content (SSC) of high quality loquat fruit can be more than 12%. In loquat fruit (cv. 'Mogi'), fructose, glucose and sucrose were reported as the major soluble sugars and the major sugar alcohol is sorbitol (Hamauzu *et al.*, 1997). Good flavor of loquat is closely related to the ratio between sugar and acid. Titratable acidity (TA) of loquat fruit with good taste ranges from 0.3 to 0.6%. Up to now, at least 10 kinds of organic acid have been detected in loquat fruit, including malic acid, lactic acid, oxalic acid, tartaric acid, pyruvic acid, citric acid, fumaric acid, isocitric acid, α-ketoglutaric acid and quinic acid, with malic acid as the dominant acid (He *et al.*, 2005). Chen *et al.* (2009) compared the organic acid content between low-acid 'Changhong 3' and high-acid 'Jiefangzhong', and found that the difference in TA between the two cultivars could be caused by the difference in malic acid concentration, which could result from a difference in NAD-malate dehydrogenase (NAD-MDH) and NADP-malic enzyme (NADP-ME) activities.

Aroma compounds are also important in contributing to the unique flavor of loquat fruit. In fresh loquat fruit (cv. 'Tanaka'), as many as 15 compounds may contribute to the aroma, such as phenylacetaldehyde, hexanal, (E)-2-hexenal, hexanoic acid, β-ionone. Among them, phenylacetaldehyde is the most potent aroma compound (Takahashi *et al.*, 2000). Color, as a visible marker of loquat fruit ripening, is related to abundant carotenoids, which are mainly responsible for the color of both peel and flesh. Zhou *et al.* (2007) analyzed color and carotenoid content of fruits from 23 loquat cultivars, among which 11 are white-fleshed and 12 red-fleshed. They found that β-carotene and lutein were the major carotenoids in the peel of both red- and white-fleshed cultivars and β-cryptoxanthin in some red-fleshed cultivars, and β-carotene were the most abundant carotenoids in the flesh. With the technique of HPLC, other species of carotenoids, such as

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neoxanthin, violaxanthin, luteoxanthin, 9-*cis*-violaxanthin, phytoene, phytofluene, and ζ-carotene were also identified. β-Carotene and β-cryptoxanthin are the most common provitamin A carotenoids, and therefore, loquat is considered to be a good source of vitamin A. Vitamin A values, as retinol equivalents (RE) of loquat flesh were 0.49 and 8.77 μg/g DW (8.46 and 136.41 μg/100 g FW) (DW = dry weight, FW = fresh weight) on average for white and red-fleshed cultivars, respectively. The RE values for the red-fleshed fruits were higher than those for other fruits such as mango, red watermelon, papaya, and orange.

In addition, phenolic compounds, including several hydroxycinnamic acid derivatives and flavonoid glycosides, were identified from loquat fruit, and these can serve as antioxidative agents of excellent value for human health (Ferreres *et al.*, 2009).

17.3 Postharvest physiology

17.3.1 Fruit physiological, physical and chemical changes

Skin color of loquat fruit becomes deeper (decrease in $h°$ value) after harvest, especially when stored at room temperature. Ding *et al.* (1998c) found that the concentration of carotenoids increased in loquat fruit (cv. 'Mogi') during the whole storage period at both room and low temperatures. The concentration of cryptoxanthin increased 2.4-fold in fruit stored at 20°C for 20 days, but fruit stored at low temperature showed a delay in change of color, indicating that low temperature can limit composition of carotenoids.

Interestingly, the firmness of loquat fruit gradually increases during storage, which is different from most other fruits. The phenomenon was found when loquat fruits were stored at low temperature, and is considered to be linked with chilling injury. Cai *et al.* (2006c) reported that firmness of loquat fruit (cv. 'Luoyanqing') also showed an increase when stored at 20°C, indicating that increase of firmness is not a specific response to low temperature. Firmness increase of loquat fruit in storage at either room or low temperature was positively correlated with lignin content, and caused by the enhanced activities of related enzymes, such as phenylalanine ammonia lyase (PAL), cinnamyl alcohol dehydrogenase (CAD) and peroxidase (POD) (Zheng *et al.*, 2000a; Cai *et al.*, 2006c).

Both SSC and TA of loquat fruit gradually decrease with increasing time of storage. Ding *et al.* (1998c) reported that total sugar concentration of loquat fruit stored at 10 and 20°C slightly increased in the first 5 days of storage and then decreased gradually, but little change was observed in the fruit kept at 1 and 5°C during storage of 30 days. Sucrose, as a major soluble sugar, declines rapidly in harvested loquat fruit, which is hydrolyzed into glucose and fructose. So, fructose and glucose changed slightly during storage. Compared with the changes in sugar, organic acids declined more rapidly, which led to the increase in the ratio of sugar and acid, and loss of fruit flavor (Ding *et al.*, 2006). Being the dominant organic acid, consumption of malic acid mainly contributed to the decline of TA (He *et al.*,

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2005). With the senescence of loquat fruit after harvest, MDA content and relative electric conductivity increase, indicating the decline of membrane integrity. Cai *et al.* (2006a) observed the accumulation of reactive oxygen species ($O_2^{\cdot-}$) in loquat fruit (cv. 'Luoyanqing') during storage at 20°C, which may be one of the main reasons for membrane damage. Further, Ding *et al.* (2006) found that activity of lipoxygenase (LOX), which is partly responsible for the production of $O_2^{\cdot-}$, increased 1.5 fold, while activity of superoxide dismutase (SOD), an enzyme for scavenging superoxides, decreased 1.5 fold in 'Wuxing' loquat fruit during storage at 25°C. The decrease of membrane integrity may cause the loss of cell compartmentation, allowing phenolic substrates to be oxidized by polyphenol oxidases. For that reason, browning usually happens at the end of storage.

17.3.2 Respiration, ethylene production and ripening

Loquat is a non-climacteric fruit. After harvest, the respiration rate of the fruit gradually declines during storage. Respiration rate is strongly influenced by storage temperature. Ding *et al.* (1998c) indicated that after storage of 4 days at 20°C, the respiration rate of loquat fruit (cv. 'Mogi') was 40 ml CO_2 kg^{-1} h^{-1}, being about 7 times higher than that (5.6 ml CO_2 kg^{-1} h^{-1}) of fruit stored at 1°C. Similarly, ethylene production in loquat fruit also showed a decline in trend with increased storage time. As a non-climacteric fruit, loquat produces relatively low amounts of ethylene (Blumenfeld, 1980). Low temperature can significantly inhibit the release of ethylene. Although loquat fruit should be ethylene-insensitive, it has been reported that ethylene treatment (100 μl L^{-1}) could significantly increase ethylene release, whereas the inhibitor of ethylene perception 1-methylcyclopropene (1-MCP) at concentration of 5 μl L^{-1} decreased ethylene production to a lower level at the beginning of storage at 20°C (Cai *et al.*, 2006d).

17.4 Physiological disorders

The main problems that cause the loss of loquat fruit quality after harvest are chilling injury, internal browning, purple spot and physical damage caused by handling and packing the fruit (Tian *et al.*, 2007).

17.4.1 Chilling injury

Low temperature storage is commonly used for loquat to extend postharvest life and inhibit fruit decay. However, loquat fruit is chilling-sensitive, and chilling injury (CI) in loquat fruit is expressed as flesh lignification, juiceless pulp, and tissue browning (Cai *et al.*, 2006a). Loquat fruit are easily injured when stored at temperatures lower than 5°C. The development of these chilling disorders has reduced consumer acceptance of this fruit and the disorders have become a major

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limitation for long-term storage of the fruit (Cao *et al.*, 2009a). Loquat fruit stored at 1–5°C have been shown to be able to maintain quality for up to 30 days (Cai *et al.*, 2006a), but the fruit showed typical symptoms of CI after three weeks of storage (Zheng *et al.*, 2000a).

The occurrence of CI was considered to be related to the abnormal metabolism of cell wall substances since the activities of pectin methylesterase (PME) and polygalacturonase (PG) declined while protopectin, lignin and fiber contents increased (Zheng *et al.*, 2000a). Meanwhile, the levels of free polyamine [spermine (SPM), spermidine (SPD), and putrescine (PUT)] in flesh changed when CI occurred. The levels of SPM decreased gradually in the first two weeks, then increased sharply and reached a peak value after three weeks. SPD decreased steadily during the first three weeks and increased significantly afterwards. The level of PUT changed in the same way as the SPM except that it increased slowly in the first two weeks. It was suggested that the increase in SPM level might be a defense response against CI, while the accumulation of PUT could be a cause of the injury and the increase in SPD level could be a consequence of chilling stress (Zheng *et al.*, 2000b). In addition, the development of CI could be the consequence of oxidative stress which may induce peroxidation and breakdown of unsaturated fatty acids in membrane lipids (Lyons, 1973).

Many strategies and treatments have been designed to reduce CI, and thus prolong storage life of fruit after harvest. Modified atmosphere packing (MAP) (Ding *et al.*, 2002a), polyamine treatment (Zheng et al., 2000b), salicylic acid application (Cai *et al.*, 2006a), and jasmonic acid treatment (Cao *et al.*, 2009a) were reported to be useful to reduce CI to various degrees, but their effect is incomplete and has implications for other aspects of fruit quality (Cai *et al.*, 2006b). Therefore, there is still a need for development of more effective techniques for loquat fruit storage (Cao and Zheng, 2008).

17.4.2 Browning

Browning is a serious problem for postharvest storage and processing of loquat fruit. The fruit turns brown rapidly when peeled or crushed. During storage, fruit browning occurs from the core area and is accompanied by lignification of the flesh tissue (Ding *et al.*, 1998b). Browning is mainly caused by enzymatic oxidation of endogenous polyphenols into quinones, which are then polymerized with other quinones and amines to form brown pigments (Ding *et al.*, 2002b). Polyphenolic compounds and polyphenol oxidase (PPO) are considered to be directly responsible for the enzymatic browning (Ding *et al.*, 2002b). Phenolic compounds are widely distributed in plants and play an important role in fruits and vegetables because they contribute to color and flavor (Spanos and Wrolstad, 1992). However, when celluar components are decompartmentalized by processing or injuries, the phenolic substrates are catalyzed by PPO to make the tissue browning and this is undesirable in fruit because of the unattractive appearance and concomitant development of an off-flavor (Friedman, 1996).

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Loquat fruits have a relatively high concentration of polyphenols. The main phenolic compounds in ripe fruit are chlorogenic acid, neochlorogenic acid, hydroxybenzoic acid and 5-feruoylquinic acid (Ding *et al.*, 1999). PPO in loquat fruits has a very high activity towards chlorogenic acid and the optimum pH and temperature for PPO activity were pH 4.5 and 30 °C, respectively (Ding *et al.*, 1998a).

In order to reduce fruit browning, PPO activity needs to be inhibited. Various compounds have been used to prevent PPO activity including sulfites, ascorbic acid and its derivatives, and thiol compounds such as cysteine (Ding *et al.*, 2002b). Sulfur dioxide (SO_2) has been used as an effective inhibitor for many years (Mayer *et al.*, 1964). However, alternative methods need to be developed because it has been reported that some people, especially asthmatics, are sensitive to sulfite (FDA, 1990; Sapers, 1993). Ascorbic and citric acids are applied in the food industry to inhibit PPO (Hsu *et al.*, 1988), but they are less effective than SO_2 because ascorbic acid is quickly consumed in the process to reduce quinones. In recent years, sulfhydryl (SH or thiol) compounds have been reported to be good inhibitors of PPO (Ding *et al.*, 1998b; Friedman and Bautista, 1995).

17.4.3 Purple spot

Purple spot is the most important physiological disorder affecting loquat fruit worldwide. More than 15% of the fruit can be damaged by purple spot, reducing external fruit quality and decreasing its commercial value by up to 40–50% (Gariglio *et al.*, 2005). This disorder occurs at fruit color break and is characterized by an extensive area of slightly depressed surface, purple in color and irregular in shape, that affects up to 30% of the exposed face of the fruit (Gariglio *et al.*, 2002). Cells of fruit with purple spot appear dehydrated, with the cytoplasm collapsed and its cellular content out of the plasmalemma. The disorder initially affects the deepest rind cell layers and then extends to all rind tissues as the symptoms increase (Gariglio *et al.*, 2002).

Sugars content has been reported to be related to this disorder. It has been shown that total sugar concentration in the flesh tissue is about two times higher than that of the rind tissue throughout the fruit growth period, and the percentage of purple-spotted fruit correlates significantly with fruit flesh sugar concentration (Gariglio *et al.*, 2003b). Combined with histological evidence, this suggests that cell dehydration of the rind tissue may be caused by an osmotic gradient between flesh and rind tissues (Gariglio *et al.*, 2000).

Calcium deficiency has also been suggested to be the cause of the disorder (Gariglio *et al.*, 2005). However, concentration of calcium in flesh fruit and epidermal tissues shows no difference between healthy and damaged fruit (Gariglio *et al.*, 2002). The specific mechanism of purple spot is still unknown. Gariglio *et al.* (2003a) reported that low temperatures at color break were correlated with purple spot incidence and that increasing the night temperatures in a greenhouse reduced the disorder. Other environmental factors including radiation, water deficit and relative humidity can also greatly affect purple

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spot (Gariglio *et al.*, 2003a). Recently, it has been considered that the incidence of purple spot is influenced by environmental factors and cultivation (Gariglio *et al.*, 2008).

17.4.4 Physical damage

Physical damage can be caused by rough handling and packing the fruit during and after harvest. Damaged fruit shows increased content of malonaldehyde, and changed respiration rate and PPO activity. These physiological changes are responsible for fruit browning (Chen *et al.*, 2003). In order to decrease physical damage, the fruit stem should be cut from the tree with a knife at harvest. Fruit should be carefully put into a basket whose inside surface is smooth and covered with soft paper to avoid mechanical injury. After harvest, fruit should be selected for appearance without physical injuries and infections and wrapped with soft paper in a paper or plastic box. It is better to package the fruit at less than 10 kg in a box, and vibration absorber sheets can be used to reduce the percentage of damaged fruit during transportation (Barchi *et al.*, 2002).

17.5 Postharvest diseases

Loquat fruit are perishable and susceptible to microbial decay. Numerous pathogens can cause decay of loquat fruits, mainly including *Colletotrichum gloeosporioides, Botrytis cinerea, Diplodia natalensis, Phytophthora palmivora* and *Pseudomonas syringae*.

17.5.1 *Colletotrichum gloeosporioides*

Anthracnose caused by *Colletotrichum gloeosporioides* is the major postharvest disease of loquat fruit. The infected fruit show small black dots in the area of infection at the beginning, then the spot enlarges gradually and the fruit become brown (Cao *et al.*, 2008). If the environmental humidity is high enough, the whole fruit may rot and the fugal fruiting bodies are formed on the rotten surface.

17.5.2 *Botrytis cinerea*

Botrytis cinerea (*Botryotinia fuckeliana*) can infect loquat fruit during growth and harvest periods. *B. cinerea* is an airborne plant pathogen with a necrotrophic lifestyle attacking over 200 crop hosts worldwide. It usually enters plant tissues at an early stage of crop development and remains quiescent for a long period. When the environment is conducive and the host physiology changes, the pathogen grows rapidly and symptoms appear. Postharvest losses of loquat due to *B. cinerea* have been reported. *B. cinerea* also causes massive losses in some field-grown horticultural crops prior to harvest, or even at the seedling stage in some hosts (Williamson *et al.*,

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2007). The blossom blight of loquat which causes the flower spike to wilt and the loquat to die has been shown to be caused by *B. cinerea* (Sun *et al.*, 2009).

17.5.3 *Diplodia natalensis*

A serious disease in loquat is collar rot and root rot caused by *Diplodia natalensis*. This pathogen can also cause postharvest rot of loquat fruit. The symptom occurs most frequently at the stem end of the fruit but occasionally can occur on the side or stylar end. The fungus grows rapidly and unevenly through the rind, which produces finger-like projections of brown tissue on the infected fruit.

17.5.4 *Phytophthora palmivora*

Phytophthora causes wilting and death of plants due to severe foot and root rot (Chern *et al.*, 1998). *Phytophthora* was firstly isolated from seedlings with symptoms of damping-off in a loquat nursery in 1980, and the fungus was subsequently identified as *P. palmivora* (Ann and Ko, 1996). However, later studies indicated that *P. parasitica* was the genus that caused disease symptoms similar to those occurring in field conditions, whereas *P. palmivora* caused only fibrous root rot of inoculated seedlings (Chern *et al.*, 1998). *P. palmivora* may play a role in the disease complex but, does not have the ability to cause severe foot and root rot alone.

17.5.5 *Pseudomonas syringae*

The bacterial strain *Pseudomonas syringae* pv. *eriobotryae* is a causal agent of stem canker of loquat. Canker usually occurs on the branches of loquat trees and is widely distributed throughout the loquat cultivation area, causing severe problems in fruit productivity (Lin *et al.*, 1999). Loquat fruit can also be infected by the pathogen after harvest through wounds caused by handling the fruit. The canker bacteria may be classified into three groups based on the production of dark brown pigment and pathogenicity to leaves of loquat plant (Kamiunten, 1990). Group A strains produce no pigment, and are not pathogenic to leaves. Strains producing no pigment but being pathogenic to leaves are classified as Group B. Group C strains are those producing a dark brown pigment, and are not pathogenic to leaves.

17.6 Postharvest treatments

17.6.1 Harvest operations

Harvest maturity has an important effect on the quality of loquat fruit. As a non-climacteric fruit, loquat should be harvested at an advanced maturity stage, since there is no significant ripening after harvest. However, in commercial

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situations, where storage, transportation and shelf-life are involved, the fruit should be harvested at the eating-ripe stage (Cuevas *et al.*, 2003) and the harvest date of most cultivars can be determined by skin color changes (Ding *et al.*, 1998c).

Loquat fruit is very fragile and should be harvested manually with great care. While harvesting, the harvesters should wear gloves, and cut fruit stems close to the fruit with shears and without pulling, then gently put them into the harvesting container. In addition, the harvesting operation should be carried out in the morning because fruit harvested then have a relatively low respiration and low fruit temperature which can shorten the pre-cooling time. While transporting harvested fruit to the packinghouse, excessive vibration will cause bruising between fruits and should be avoided.

17.6.2 Packinghouse practices

Packinghouse operations include a series of handling practices such as dumping, pre-sorting, decay controlling, quality grading, pre-cooling and boxing. Providing shade during the packing operations is extremely important and the whole process should be carried out carefully. After harvested fruit are delivered to the packinghouse, the first step, known as dumping, is to remove the fruit from the harvesting container. The next step is pre-sorting, i.e. removing injured, decayed or otherwise defective fruit.

Removing decayed produce can limit the spread of infection, especially when postharvest pesticides are not used. In order to control the postharvest decay during storage and shelf life, fruit may be required to be treated with some chemicals. After that, the fruit will be sorted according to size and color. If the fruit is directly sold in a local market, it can be packed and transported right away. For storage, loquat fruit needs to be pre-cooled. Pre-cooling should be carried out within 6–8 hours after harvest. Room cooling is a relatively low cost method but very slow, so forced-air cooling or other fast cooling methods are recommended. After pre-cooling, the fruit temperature should be maintained close to the ideal storage temperature. Then, fruit are boxed and stored. The optimal storage temperature may change from 0 to 10°C depending on different varieties and can provide storage time of 30 days.

17.6.3 Control of ripening and senescence

As temperature has a significant effect on the respiration and ethylene production, storage at low temperature can effectively delay the senescence of loquat fruit after harvest. The effective storage life of loquat fruit (cv. 'Mogi') at 10°C is 15 days, and only 10 days at 20°C. However, good fruit quality can be maintained for up to 30 days at 1 and 5°C (Ding *et al.*, 1998c). Treatment of 1-MCP can delay significantly the postharvest decrease in firmness, maintain cell membrane integrity, decrease oxidation of polyphenols, and reduce browning at both room

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and low temperatures (Cai *et al.*, 2006d). Storage in controlled atmosphere (CA) conditions (10% O_2 + 1% CO_2) is effective in reducing fruit SSC/TA and maintaining normal flavor, and can extend the storage life to at least 50 days (Ding *et al.*, 2006), while the ideal concentrations of O_2 and CO_2 may be varied according to different varieties.

17.6.4 Decay control

The first line of defense against postharvest decay is preharvest management. Some pathogens (such as *Colletotrichum acutatum*) in loquat fruit are latent infection, and keeping free from the infection in the field can improve control. The second important defense is careful handling and packaging during and after harvest, because damaged areas caused by rough handling are easily infected by pathogens. Meanwhile, sorting out damaged or decaying fruit is important to limit the disease occurrence during storage. Some storage conditions mentioned above, such as low temperature, MAP and CA can also reduce decay (Ding *et al.*, 2006). Yet, sometimes loquat fruit needs to be treated with additional measures to control postharvest diseases. Some anti-fungal chemicals can be used by dipping after harvest and before storage. Gu *et al.* (2007) reported that three fungicides, Sportak, Sporgon and Mancozeb, could effectively control the main postharvest diseases in loquat fruit.

However, growing concerns about public health and the environment, and increasing resistance of many fungi to commonly used fungicides have stimulated the search for alternative biocontrol methods (Tian, 2006). Application of the biocontrol agent *Pichia membranaefaciens* (Cao *et al.*, 2008a) or combined with calcium salts (Cao *et al.*, 2008b) and methyl jasmonate (MeJA) (Cao *et al.*, 2009b) could effectively reduce postharvest anthracnose rot caused by *Colletotrichum acutatum* in loquat fruit, which could be an alternative to chemical fungicides for control of postharvest disease in loquat fruit. Recently, Gao *et al.* (2009) reported that short-term pre-storage N_2 treatment (100% N_2 for 6 h at 20°C) was effective in controlling the postharvest decay in a small scale test. Additionally, MeJA treatment has been proved to be effective at inhibiting anthracnose rot and maintaining quality in loquat fruit, because of resistance induced in loquat fruit by MeJA (Cao *et al.*, 2008c). Non-chemical and inexpensive postharvest technologies are worth developing for commercial application.

17.6.5 Recommended storage and shipping conditions

Low temperature (1–5°C) is the most commonly used condition for long-term storage. The optimum temperature varies according to different loquat cultivars. MAP and CA technologies can expand the storage time. After storage, the fruit are commonly re-packed and transported to market destinations. For long distance transportation, a refrigerated car or container is required. For short distance transportation, temperature control measures can be used, such as shipping in an insulated car, and packing in a foam box with/without ice.

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17.7 Storage technologies

Loquat fruits mature in the hot and rainy season and have a short postharvest life at ambient temperature since they are juicy and perishable, easily damaged and tending to lose moisture, as well as susceptible to microbial decay, resulting in quality deterioration after harvest. Therefore, it is difficult to store loquat fruit for a long period of time. Storage techniques used for loquat fruit usually include the following.

17.7.1 Low temperature storage

In general, loquat fruit kept in air at room temperature after harvest can be maintained for about 6–9 days. Low temperature is widely used to store loquat fruits because of its effectiveness in inhibiting the physiological metabolism, reducing pathogenic decay and keeping quality (Tian *et al.*, 2007). The optimal storage temperature for loquat fruit is dependent on different varieties and changes from 0°C to 10°C. For example, the fruits of 'Jiefangzhong' and 'Zaozhong 6' are usually kept at 6–8°C and 8–10°C (He *et al.*, 2004), and 'Wuxing' may be stored at 1 °C (Ding *et al.*, 2006), with acceptable storage time of 30 days. Ding *et al.* (1998c) reported that fresh fruit quality of 'Mogi' loquat could be maintained for up to 30 days at 1 and 5°C, and the effective storage life at higher temperatures was 15 days at 10°C and 10 days at 20°C. Low temperatures of 0–5°C could significantly reduce fruit respiration, reduce ethylene production and maintain fruit quality during storage, so that the recommended commercial storage temperatures of loquat fruit are from 0 to 5°C with >90% RH.

Loquat fruits are sensitive to low temperature injury (chilling injury, CI) in invariable low temperature conditions. Wang (1993) considered that fruits conditioned by exposure to temperatures slightly above the critical chilling range had more resistance to subsequent lower temperatures. Low temperature conditioning (LTC) is an alternative technique for increasing the tolerance of loquat fruit to low temperatures. The crucial factors of this technique are temperature differences between conditioning and storage temperature and the duration of the conditioning treatment. LTC as conditioning at 5°C for 6 days before 0°C storage effectively alleviated CI of 'Luoyangqing' fruit, and reduced lignin content and browning index, and retarded the decrease of juice during storage (Cai *et al.*, 2006b). Their results indicated that LTC treatment doubled the low temperature storage life of loquat fruit for a shelf life of 5 days. LTC is considered to be an effective commercial treatment, since it is beneficial for maintaining acceptable external and internal quality of loquat fruit, extending low temperature storage life and allowing harvesting of near-ripe fruit with better quality characteristics (Cai *et al.*, 2006b).

17.7.2 Modified atmosphere packaging

Modified atmosphere (MA) is a term used to designate any synthetic atmosphere, and often is used to make adjustments in gas composition during storage or

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transportation. Modified atmosphere packaging (MAP) is effective in adjusting the atmosphere compounds around the fruit by fruit respiration and is widely used to keep fruit in a relatively lower O_2 and higher CO_2 atmosphere, which is beneficial for extending the fruits' postharvest life by reducing the rate of respiration and diseases, as well as preventing water loss and maintaining fruit quality. The compounds of storage atmosphere are important for the storability of loquat fruit. The concentrations of CO_2 and O_2 of loquat fruit maintained in polyethylene (PE) bags changed with storage temperature. Inside PE bags, higher CO_2 and lower O_2 concentration were accumulated at 20°C compared with that at 5°C, and ethylene concentration was also higher at 20°C than that at 5°C in PE bags (Ding *et al.*, 2002b). The researchers found that PE with a higher gas permeablity showed a lower incidence of decay at 20 and 5°C, and fruit in 20–30 µm-thick PE bags could be stored for up to 2 months with acceptable quality and minimal risk of decay at 5°C, and PE bags could effectively minimize decreases in organic acids of loquat fruit during storage periods as compared with perforated polyethylene (PE-pf) bags (Ding *et al.*, 2002b). In the experiment, we found that MAP with 13–18% O_2 and 2–4% CO_2 could significantly prolong storage time of the loquat fruit (cv. 'Wuxing') kept at low temperature conditions as compared to the control at 25°C, and packaged in PE bags, the fruit showed a notably lower decay index and weight loss at 1°C than that at 6°C (see Fig. 17.1) (Ding *et al.*, 2006).

Moreover, fruit in perforated or higher permeance PE bags had higher levels of carotenoid compared with those in low gas permeance bags. Internal browning and brown surface spotting occur during long-term or high CO_2 storage (Ding *et al.*, 1999). The decay of loquat fruit was caused predominantly by an internal flesh browning followed by complete rotting.

17.7.3 Controlled atmosphere conditions

Controlled atmosphere (CA) means a close control of gases around fruits, which can maintain the synthetic atmosphere. The effects of exposure to superatmospheric O_2 concentration on respiration and ethylene production may depend on the commodity, maturity and ripeness stage, O_2 concentration, storage time and temperature, and concentrations of CO_2 and C_2H_4 present in the atmosphere (Kader and Ben-Yehoshua, 2000). On regulating the atmosphere composition, CA is more accurate and effective at inhibiting pathogen growth than MAP. The storability of loquat (cv. 'Wuxing') fruit stored in CA conditions was better than that in MAP at 1°C. Fruits kept in CA-I (10% O_2 + 1% CO_2) and CA-II (70% O_2 for 24 hours, then 10% O_2+1% CO_2) showed a lower decay index as compared to that in MAP (see Fig. 17.2). After 50 d of storage at 1 °C, CA fruits had a decay index of 5–7% with normal flavor, while the decay index of MAP fruit was 17% (Ding *et al.*, 2006), indicating that CA storage is beneficial for prolonging storage time and maintaining fruit quality. In addition, a short term, high-O_2 treatment at the beginning of storage had little effect on fruit flavor, but stimulated ethanol accumulation in loquat fruit, and reduced activities of PPO, POD, PAL, endo-PG and exo-PG (Ding *et al.*, 2006).

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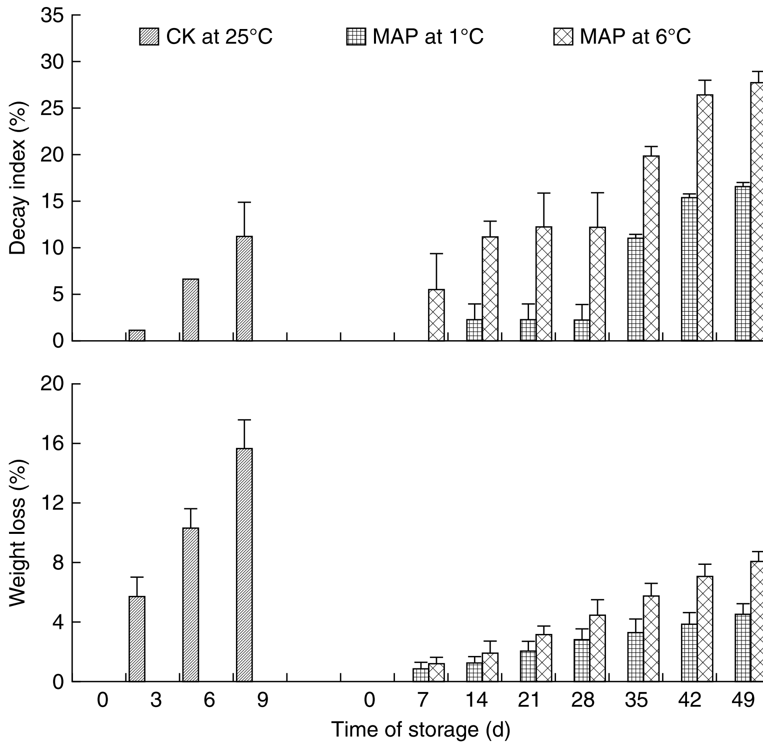

Fig. 17.1 Decay index and weight loss of loquat fruit (cv. 'Wuxing') in different storage conditions during storage periods.

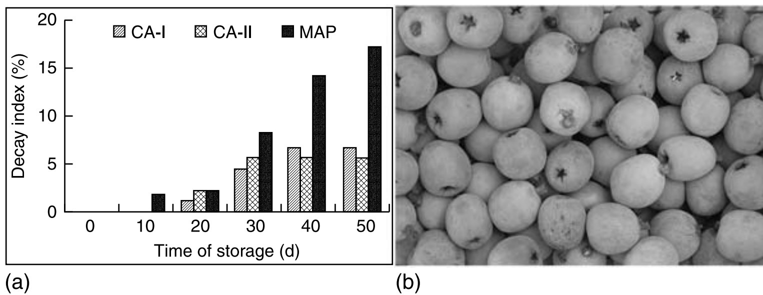

Fig. 17.2 (a) Decay index of loquat fruit (cv. 'Wuxing') in CA and MAP at 1 °C during storage periods; (b) loquat fruit stored at CA for 50 days.

17.7.4 Hypobaric pressure storage

Hypobaric pressure (HP) treatment as a storage technique, characterized by reduced oxygen level, lowered pressure and quickened heat removal, has been proved to significantly delay ripening and senescence, and extend shelf-life of

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fruit. Gao *et al.* (2008) reported that loquat fruit kept under 40–50 kPa hypobaric pressure conditions at 5°C for 49 days showed a significant decrease in the rates of respiration and ethylene production as compared to low temperature storage. They found that hypobaric storage significantly inhibited browning index, and maintained a high content of total soluble solids, total titratable acidity and vitamin C, and inhibited POD and PAL activities of loquat fruit. Thus, hypobaric pressure in combination with low temperature is a feasible storage technique because of its effectiveness in maintaining quality of loquat fruit in storage.

17.8 Conclusions

As compared to some large fruits (apple, pear, citrus, peach, etc.), loquat, as a summer-harvested small fruit, needs further research on its characteristics and postharvest treatment technology. According to the physiology and quality characteristics of loquat fruit, future research needs include the following.

17.8.1 Studies on mechanism of fruit ripening and resistance based on molecular and proteomic levels

Previous studies have mainly been conducted on the roles of some enzymes, such as cell wall hydrolases (polygalacturonase, xyloglucan endotransglycosylase, cellulase, pectin esterase, β-galactosidase), PR-related enzymes (PPO, POD, PAL, chitinase, β-1, 3-glucanase) and antioxidant enzymes (CAT, SOD) during softening of harvested fruit. However, these enzymes may not be the sole determinants in fruit ripening and resistance, because genetic modification of enzyme activities has often not greatly delayed fruit ripening or affected fruit resistance in many cases. Recently, Yang *et al.* (2008) cloned four expansin genes, i.e. *EjEXPA1, EjEXPA2, EjEXPA3* and *EjEXPA4* from loquat fruit, and proved that *EjEXPA1* might be associated with chilling-induced lignifications, while both *EjEXPA1* and *EjEXPA4* were closely related to softening of loquat fruit during the postharvest period. Additionally, a proteomic approach has been used to point out the mechanisms of ripening regulation and resistance in peach (Chan *et al.*, 2007), sweet cherry (Chan *et al.*, 2008), apple (Qin *et al.*, 2009) and jujube fruit (Wang *et al.*, 2009) in our lab. Consequently, using new research approaches will be helpful in investigating the mechanisms of chilling injury, senescence and resistance in loquat fruit.

17.8.2 New integrative technologies for control of decay and chilling injury

After harvest, loquat fruit are very perishable and susceptible to mechanical injury and microbial decay. In general, chilling injury can reduce the resistance of the fruit against pathogens, resulting in accelerating decay in storage. At present, postharvest diseases caused by fungal pathogens in fruits are primarily controlled by the use of synthetic fungicides. However, it is important to note that application

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of fungicide may reach the maximum amount permitted by law when the fruit is packed for export. Lately, applying antagonist yeast has shown an effective control for decay of loquat fruit in lab experiment (Cao *et al.*, 2008a; 2008b), indicating that biological control can be an alternative to chemical fungicides for control of postharvest diseases in loquat fruit. As antagonistic yeasts alone could not provide commercially acceptable control of fruit decay, new integrative technologies, particularly in commercial treatment, should be developed in order to effectively maintain quality and enhance marketing value of loquat fruit.

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Plate XXIX (Chapter 16) Arils of longan cv. 'Shixia' grown in Guangdong province, China.

Plate XXX (Chapter 17) Loquat fruits (*Eriobotrya japonica* Lindl.) of different varieties: (a) 'Jinwuxing'; (b) 'Jiefangzhong'; (c) 'Zaozhong 6'; (d) 'Dahongpao'.

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Plate XXXI (Chapter 17) Different processed products of loquat fruit: (a) loquat juice; (b) loquat wine; (c) loquat jam; (d) loquat ointment; and (e) loquat tea.

(a)

(b)

(c)

(d)

Plate XXXII (Chapter 18) (a) Exterior of the lucuma fruit; (b) interior of the lucuma fruit; (c) Lucuma fruit showing physical injury; (d) Lucuma fruit and juice

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18

Lucuma (*Pouteria lucuma* (Ruiz and Pav.) Kuntze)

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Abstract: Lucuma fruit is a good source of fiber, minerals, β-carotene, phenolics and niacin. The fruit is consumed mostly in Peru and Chile, although it is also known in a few other countries, and mostly in processed form in ice creams, bakery products and preserves. Almost no postharvest information is available on this fruit, and research is needed on nearly all aspects of fruit physiology and handling. This brief chapter is intended to report the information available on this fruit and to draw attention to the research that needs to be carried out and the information that needs to be generated.

Key words: *Pouteria lúcuma*, postharvest, nutrition, processing, handling.

18.1 Introduction

The lucuma tree is not a tropical plant, rather it grows at temperate elevations in dry locations. Native to Peru, it is a favorite ice cream flavor. Most of the crop is usually used in dehydrated or frozen form since the soft flesh of the fresh fruit is easily damaged, making transportation difficult.

18.1.1 Origin, botany, morphology and structure

Lucuma (*Pouteria lúcuma*) belongs to the Sapotaceae family and is also known as lucma, lucmo, lúcuma, lúcumo, mammon, cumala, rucma or marco. It is a native fruit of the highlands of Peru, Ecuador, and Chile and was an important part of the pre-hispanic diet of the people from these areas. It grows well in Mexico and Hawaii but the fruit is not very popular in these areas.

The lucuma tree is an evergreen with a height of 8 to 15 m and a dense crown with branches that produce white latex. It has a long juvenile period of about

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15 years. It is propagated by grafting scions onto seedling rootstocks, but this method causes high variability in production. Propagating leafy cuttings under mist or in a plastic hermetic chamber can also be successful (Duarte, 1990). *In vitro* propagation has been attempted by using shoot tips, but the majority of the plants died after transfer to greenhouse conditions (Jordan and Oyanedel, 1992). On the other hand, micropropagation of lucuma plants combined with inoculation with arbuscular mycorrhizal fungi has been shown to improve their growth and development (Padilla *et al.*, 2006).

Lucuma fruit has an ovoid to elliptical shape with a pointed or depressed apex. (See Plate XXXII in the color section between pages 274 and 275.) It is 7.5–10 cm in size with thin skin which is greenish-yellow when the fruit is fully ripe. The flesh is dry, with a starchy orange-yellow color and pumpkin-like sweet flavor. The unripe fruit contains latex. Often, two seeds are found, although 1–5 are possible. They are round to oval in shape, dark brown with a glossy appearance and a white hilum. Germination of lucuma seeds is affected by dessication (below 19% matter content), thus a less drastic dessication process should be used when storing lucuma seeds (Magne Ojeda *et al.*, 2005). The most common varieties are 'Seda' and 'Palo'. The former is mainly consumed fresh due to the higher water content, while the latter is used to make ice cream.

18.1.2 Worldwide importance

Peru is the main producer of lucuma (88% of world production), although production in Chile has been increasing (12%). Introduction of this species to the US has not been successful, especially because the lucuma tree is very sensitive to freezing temperatures. In 2010, lucuma from Peru was mainly exported to Chile (74%), followed by the US and Canada (AMPEX, 2010). It is almost unknown outside these areas, although it can be found in countries like Costa Rica, Mexico and Hawaii. The fruit is exported mainly as frozen pulp (79%) and flour, which are used in bakery products, ice cream and jams (AMPEX, 2010).

18.1.3 Culinary uses, nutritional value and health benefits

The lucuma can be eaten raw, although some people find the raw fruit not very appealing since it has an odd aftertaste. The pulp is made into preserves or used in ice cream, yogurt, many desserts or bakery products, for example in pastries and as a cookie filling. Lucuma flavor ice cream is very popular in Peru. Since lucuma gives a sweet taste to the foods to which it is added, it is a healthy natural alternative to sweeteners. In spite of the sweet taste, lucuma has a low sugar concentration. Lucuma fruits are a good source of fiber, vitamins and minerals. Fiber in lucuma is mainly found in the insoluble form (Glorio *et al.*, 2008). High concentrations of β-carotene, niacin and iron have been found in the fruit. Some of the sugars present in lucuma fruit are glucose, fructose, sucrose and inositol in the following amounts: 8.4, 4.7, 1.7, and 0.06 g, respectively (Herbal Guides, 2010). The nutritional value of lucuma fruit is presented in Table 18.1.

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Table 18.1 Nutritional value of lucuma fruit (per 100 g of fruit)

Constituent	Approximate value
Water content	62 %
Calories	143.8
Protein	2.3 g
Carbohydrates	33.2 g
Fat	0.2 g
Fiber	1.1 g
Calcium	16 mg
Phosphorus	26 mg
Iron	0.4 mg
Thiamin	0.01 mg
Riboflavin	0.14 mg
Niacin	1.96 mg
Vitamin C	5.4 mg

Source: http://www.guallarauco.cl (2010)

The antioxidant capacity of lucuma extracts was found to be high. Catechin and epicatechin, present in these extracts, may contribute to the observed antioxidant capacity (Ma, 2004). A recent study found aqueous extracts of lucuma to have the highest concentration of phenolic compounds (11.4 mg g^{-1} dw) when compared to other Peruvian fruits and a high α-glucosidase inhibitory activity. The latter could suggest lucuma as a food-based treatment to complement diabetes management (Silva Pinto *et al.*, 2009). The growth of *Staphylococcus aureus* was inhibited by extracts of lucuma (Lazo, 1990). Lupeol and a and β-amyrin in the form of fatty acid esters and acetates, as well as the cyanogenic glycoside lucumin, have been identified in seeds of lucuma from Belize (Merfort, 1984).

18.2 Fruit development and postharvest physiology

18.2.1 Fruit growth, development and maturation

The growth of lucuma fruits is sigmoidal and is accelerated by higher temperatures (Sandoval, 1997).

18.2.2 Respiration, ethylene production and ripening

Lucuma is a climacteric fruit according to its CO_2 production pattern (Yahia, 2004). Ripening of the fruit includes changes in color from green to yellow, loss of firmness and an increase in soluble solids. Intense respiration and sugar accumulation are characteristic during ripening of lucuma (Lizana *et al.*, 1986; Yahia, 2004).

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18.3 Maturity and quality components and indices

One of the most common maturity indices used for lucuma is the change in skin color from green to yellow, although pulp color can vary from green to yellowish green and light yellow to orange-yellow color (Lizana, 1980). Alternatively, soluble solids content may be used as a maturity index. However, because of the low water content and density of the pulp, it is necessary to homogenize it in water in order to disrupt the pulp and get an accurate value (Lizana, *et al.*, 1986).

Based on peel and pulp color, texture, soluble solids content and respiration, five maturity stages have been developed (Table 18.2). Fruit of lucuma var. 'Palo' have 0.11% acidity and 8°Brix at maturity (Glorio *et al.*, 2008).

Table 18.2 Classification of lucuma fruit into different maturity stages on the basis of peel and pulp color

Class	Peel color	Pulp color
1	Light yellow	Light yellow
2	Light green	Creamy yellow
3	Yellow-green	Yellow
4	Green-yellow	Dark yellow
5	Green-yellow	Orange-yellow

Source: Lizana (1980)

18.4 Postharvest handling factors affecting quality

18.4.1 Temperature management

The quality of lucuma fruit stored at 7 °C is not affected when the storage duration is up to 7 days. After longer periods of storage, fruit do not ripen uniformly. If stored at 13 and 18 °C, fruit can be kept for up to 14 days before showing signs of decay (Sandoval, 1997).

18.4.2 Physical damage

The soft texture of lucuma fruit makes it very prone to physical damage (Plate XXXIIC), and because of that, lucuma is commercialized as frozen pulp or flour.

18.4.3 Water loss

Lucuma fruit is highly sensitive to water loss postharvest (Sandoval, 1997).

18.5 Physiological disorders

As mentioned above, storage of lucuma fruit at 7 °C for more than 7 days negatively affects fruit ripening and quality (Sandoval, 1997).

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18.6 Insect pests and their control

As the lucuma tree is only affected by a few pests, it is a good candidate for organic production. Trees are sometimes periodically washed with pure water to keep them free of pests.

18.7 Postharvest handling practices

18.7.1 Harvest operations

Lucuma trees start producing fruit after 4 or 5 years and provide fruit year-round. It is common to see ten-year-old trees producing 200-300 fruit per year (Prolucuma, 2010). Although mature fruit fall from the tree they still need to ripen for several days before they can be consumed.

18.7.2 Control of ripening and senescence

Irradiation of lucuma ($5–100 \times 10^3$ rad) barely affects the respiratory rate of the fruit and the shelf life is not significantly extended. Chemical parameters such as total sugars, water content, ash and vitamin C are not affected by irradiation, except that acidity increases slightly. Irradiation treatment at higher than 5000 rad causes loss of quality, making the fruit unacceptable for consumption. A strong fungicidal effect is seen when fruit are treated with more than 5000 rad (Díaz *et al.*, 1969).

18.7.3 Recommended storage and shipping conditions

Storage at low temperatures for more than 7 days negatively affects ripening. Temperatures of 13 or 18 °C can be used to store lucuma fruit for up to 14 days. Due to its high sensitivity to water loss, the fruit need to be kept at high relative humidity (Sandoval, 1997). Modified atmosphere (especially for packaging) could be helpful in maintaining the quality of fresh fruit (Yahia, 1998; 2008).

18.8 Processing

Lucuma products available in the market include puree and pulp (Plate XXXIID). These products are made from fruit that have been washed, disinfected, peeled and seeded. The pulp is ground, vacuum-packed and quick frozen at −25 °C. This way the pulp is stable for 2 years without significant changes in quality. This product is used in drinks, ice cream and baking. Lucuma jam is made by mixing the pulp with cooked sugar; the product is vacuum-packed in polyethylene (PE) bags inside corrugated cardboard boxes of 20 kg each. Pulp processed in this way is stable for 1–2 years at −18 °C (Guallarauco, 2010; Prolucuma, 2010).

Freeze-dried pulp is also available. Freeze-drying preserves the flavor characteristics better than dehydration. The fruit is washed, disinfected, peeled,

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seeded and cut before being frozen, lyophilized and ground. The final product is packed in PE bags of 40 kg (Prolucuma, 2010).

Flour produced from dehydrated lucuma fruit is used as a flavoring agent in ice creams or dairy products. The fruit is selected, disinfected, peeled, seeded and cut, before being dried at 60 °C in hot air tunnels. Lucuma flour is packed in 10-kg bags (Prolucuma, 2010).

18.9 Conclusions

Although fresh lucuma is little known outside its area of origin, processed products such as flour and frozen pulp are available in different markets. Handling of fresh lucuma is difficult because the fruit is very prone to physical damage. The high content of some nutrients such as β-carotene, niacin and iron makes lucuma a good choice especially in areas where deficiency of these nutrients is frequent.

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Plate XXXI (Chapter 17) Different processed products of loquat fruit: (a) loquat juice; (b) loquat wine; (c) loquat jam; (d) loquat ointment; and (e) loquat tea.

(a)

(b)

(c)

(d)

Plate XXXII (Chapter 18) (a) Exterior of the lucuma fruit; (b) interior of the lucuma fruit; (c) Lucuma fruit showing physical injury; (d) Lucuma fruit and juice

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19

Macadamia (*Macadamia integrifolia, Macadamia tetraphylla* and hybrids)

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Abstract: Macadamia is a rainforest tree indigenous to Australia that is grown commercially for its edible nuts. This chapter discusses quality and the key preharvest and postharvest practices that impact on macadamia quality. The chapter first reviews botany, the macadamia industry, fruit development, and measures of quality, such as oil content, quality defects, appearance and rancidity. Preharvest impacts on quality such as cultivar, site, crop management and pests and diseases are considered. Key postharvest processes that are crucial for macadamia quality such as harvest methods, drying, postharvest handling and factory processing are also reviewed.

Key words: Macadamia, drying, postharvest handling, oil content, quality defects macadamia harvesting.

19.1 Introduction

19.1.1 Origin, botany, morphology and structure

Macadamia F. Muell. is a member of the predominantly Southern Hemisphere family Proteaceae and is cultivated for its edible kernels. There are four species of *Macadamia*, and all occur in subtropical rainforests along the east coast of Australia (Douglas, 1995; McDonald and Ismail, 1995; Mast *et al.*, 2008). Commercial macadamia cultivars were developed from the two edible species, *M. integrifolia* Maiden and Betche and *M. tetraphylla*, and their hybrids (Gross, 1995). The other two species, *M. ternifolia* and *M. jansenii*, are inedible as they contain cyanogenic glycosides (Dahler *et al.*, 1995). *M. jansenii* is now critically endangered with less than 50 individuals known in the wild. *M. integrifolia* is characterised by round nuts with a smooth shell, three leaves at each node and leaf margins without spines, and is found only on the east coast between 25.5°and 28.3°S. *M. tetraphylla* has a more southerly distribution (27.6°–29°S) and is

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distinguished by spindle shaped, rough shelled nuts, four leaves at each node and serrated, spiny leaf margins (Gross, 1995; Nagao and Hirae, 1992).

Botanically, the macadamia fruit is a follicle (Strohschen, 1986). Macadamia fruits consist of the pericarp, (known commercially as the husk), the testa (or shell) and the embryo (or kernel). (See Plate XXXIII (a), (b) and (c) in the colour section between pages 274 and 275.) Macadamia fruit (or nut-in-husk) fall to the ground at maturity and are harvested by hand or mechanically from the ground. The fibrous pericarp (husk) is removed by a mechanical dehusker. Nut-in-shell (botanically, the seeds) are then dried to 10% moisture content, transported to the factory for processing, further dried to 3% moisture content, cracked and processed. The kernel has an oil content of 70–80% (Trueman *et al.*, 2000). The mature embryo of macadamia comprises the edible 'kernel' (Strohschen, 1986) (Plate XXXIIIC). 'Nut' or the commercial term 'nut-in-shell' is used to refer to the seed, i.e., the seed coat or 'shell' containing the embryo, or 'kernel'.

19.1.2 Worldwide importance and economic value

The macadamia is the only Australian plant that has been domesticated on a commercial scale as a food crop. Macadamia is cultivated mainly in Australia, the US (in Hawaii and California) and South Africa. There are also expanding industries in Brazil, Guatemala and Kenya, and smaller industries in New Zealand, Malawi, Paraguay and other countries. World production for 2009 was projected to be over 26 000 tonnes of kernel, with Australia producing 10 500, South Africa 5 600 and Hawaii 3 750. In Australia, macadamia nut production has grown from a modest 4 400 tons in 1987 to above 37 500 tonnes of nut-in-shell in 2009 (ABS 2009a). Current annual value of macadamia exports from Australia is estimated at $A20.1 million for nut-in shell and $A64.5 million for kernel in 2008, making it one of Australia's most valuable export horticultural products (ABS 2009b,c).

Macadamia cultivars are primarily propagated by grafting, and all scions within a cultivar have the same genotype. The Hawaii Agricultural Experimental Station (HAES) commenced a cultivar selection programme from only a handful of seed taken to Hawaii in 1881. Hawaiian cultivars still form the basis for the industry worldwide, and many of the widely grown cultivars worldwide still bear the prefix HAES (Ito *et al.*, 1983). In Australia, two HAES cultivars, 344 and 741, are the most commonly grown. Recently, breeding programmes have focused on cultivars selected for local conditions, and some of these, such as 'Hidden Valley A16', have been widely planted.

19.1.3 Culinary uses, nutritional value and health benefits

Macadamia kernels are eaten raw, used as a cooking ingredient or processed into a variety of products. Popular products include roasted, roasted and salted, chocolate coated, honey-roasted and wasabi-flavoured. They are also used as ingredients for biscuits, cakes and ice cream, processed into a paste and cold

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pressed to produce an oil. Macadamia oil is used both as cooking oil and as an ingredient for food and cosmetics.

The macadamia kernel has a protein content of around 9.2% of dry material and 4.22–4.75% of total sugar, most of which is sucrose, a non-reducing sugar (Cavaletto, 1983; Fourie and Basson, 1990). The kernel is very rich in oil, ideally containing 75–80% by weight of oil for *Macadamia integrifolia* and slightly less for *Macadamia tetraphylla* (Cavaletto, 1983; Trueman *et al.*, 2000). Macadamia oil is one of the most highly mono-unsaturated oils available (Ako *et al.*, 1995). Oleic acid is the predominant fatty acid (c.60%), with smaller quantities of palmitoleic (c.22%), palmitic (c.9%), stearic (c.2%) and linoleic (c.2%) acids (Jones, 1937; Saleeb *et al.*, 1973). This high degree of unsaturation has an important bearing on the storage characteristics, as monounsaturated oils are less subject to oxidation than poly-unsaturated oils (de Man, 1990).

Regular consumption of monounsaturated fats is associated with lower blood cholesterol and there is evidence to show that regular consumption of macadamia nuts can reduce cholesterol and help to reduce the risk of coronary artery disease. Even short term consumption can improve the biomarkers of oxidative stress, thrombosis and inflammation and lower cholesterol (Garg *et al.*, 2003; 2007). Serum concentrations of total cholesterol and LDL cholesterol were lower for subjects on a cholesterol-lowering diet that included macadamia nuts compared to a diet that did not, indicating that macadamia nuts can help to reduce the risk of cardiovascular disease (Griel *et al.*, 2008).

19.2 Preharvest physiology

19.2.1 Fruit growth and development

Macadamia produces many flowers in spring each year and requires cross pollination for fertilization and fruit set (Sedgley, 1981; Wallace *et al.*, 1996). Flowers are borne on racemes of 200–300 flowers and commonly only one or two mature fruit are produced on each raceme. The ovary of macadamia contains two orthotropous ovules at anthesis (Strohschen, 1986). Usually, only the larger of the two ovules is fertilized (Sedgley, 1981; Strohschen, 1986). When both ovules are fertilized, two hemispherical fruits develop (Francis, 1928) and their shape predisposes the kernel to severe damage during processing. Fruit diameter of macadamia increases rapidly at 2–3 weeks after anthesis until 12–15 weeks (Nagao and Hirae, 1992). Fresh fruit growth follows a simple sigmoidal curve, with weight increasing rapidly at 5 to 6 weeks after anthesis and reaching a maximum at 18 weeks (Sakai and Nagao, 1984). Fruit growth slows at about 15 weeks, coinciding with the hardening of the outer integuments (Stephenson and Gallagher, 1986; Nagao and Hirae, 1992). By around 20 weeks after anthesis, the cellular endosperm is completely replaced by the cotyledons (Hartung and Storey, 1939). Fruit enlargement is completed by this time and oil accumulation commences (Jones, 1937; Sakai and Nagao, 1984; Strohschen, 1986). Oil is contained in all cells of the embryo (Francis, 1928). Oil accumulation of

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macadamia kernels is accomplished well before abscission (Baigent, 1983; Trueman *et al.*, 2000).

19.2.2 Mature fruit structure

The husk (pericarp) of the macadamia fruit is described as fibrous and horny (Cavaletto, 1983; Strohschen, 1986). The characteristic resilient, dense nature of the husk of macadamia (Plate XXXIII(a)) results from its fibre content. At maturity the pericarp dries and splits along the single suture (Plate XXXIII(b)). The husk does not dehisce until after abscission in most cultivars (Strohschen, 1986; Trueman *et al.*, 2000). The husk requires mechanical force for removal, an operation that may cause damage to the kernel.

The hard testa or shell (Plate XXXIII(b)) is composed of the integument of the fertilized ovule. The outer integument achieves extreme thickness due to cell divisions and branching of the vascular system (Strohschen, 1986). The hilum is located towards the apex of the embryo. It joins the pericarp near its suture, adjacent to the stylar end (Francis, 1928). The micropyle is found towards the opposite end of the seed (Plate XXXIII(c)). The micropyle is highlighted by a trace of white enamel protruding from it (Francis 1928; Plate XXXIII(b)). A natural fissure or suture exists along the line joining the hilum and micropyle. At the micropylar end of the ovule, the inner epidermis of the outer integument is 5–7 layers thick, producing the distinctive enamel-like layer of the testa (Hartung and Storey, 1939; Strohschen, 1986). Mature embryos may cling to this enamelled area, possibly due to the presence of the vestigial inner seed coat (Hartung and Storey, 1939). This adhesion to the enamelled area may be the major cause of ‘shoulder damage’ in macadamia. At the hilum end of the fruit, the inner integument completely disintegrates apart from a few lignified remnants of cells, and the shell of macadamia is lined with small, flattened, slightly lignified cells which are dark-staining, giving this region its smooth, brown layer (Strohschen, 1986). Francis (1928) termed these two layers the tegmen, or inner seed coat. These contrasting layers produce the characteristic bi-coloured internal appearance of macadamia testa (Plate XXXIII(c)).

The mature macadamia embryo consists of two massive cotyledons, and the embryo unit is inserted between them (Francis, 1928; Strohschen, 1986; Walton and Wallace, 2005a). At maturity the cotyledons have completely enclosed the radicle and extend into the micropyle (Walton and Wallace, 2005a). Oil and protein bodies are prominent in the mature tissue of the cotyledons and oil is stored in oil bodies in the cells of the parenchyma (Walton and Wallace, 2005a). Macadamia can contain as high as 80% oil and the macadamia is the highest oil-yielding ‘nut’ on the market (Jones and Shaw, 1943; Strohschen, 1986; Trueman *et al.*, 2000).

19.3 Quality components and indices

The macadamia has achieved a reputation as one of the most highly regarded nuts in the world (Nagao and Hirae, 1992). Quality has been described as the

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combination of all the characteristics that give the product value or 'a degree of excellence' and includes aspects of appearance, flavour and texture (Evans and Hofman, 2005). The International Macadamia Quality Standard describes the quality of macadamias as being judged by the buyer/consumer and being essentially the delicate characteristic flavour, crunchy texture and freshness (O'Hare *et al.*, 2000). Quality of the product is a strong driver of commercial returns to both growers and processors and maintaining quality is a major challenge for the macadamia industry worldwide.

Commercial processors calculate price for consignments of nuts based on three parameters: (1) kernel recovery, calculated as the ratio of kernel to nut-in-shell; (2) percentage of grade 1 kernel, i.e., percentage of nuts with greater than 72% oil content; (3) percentage of unsound kernel, i.e. percentage of nuts that have quality defects. Quality defects include shrivelled appearance (often associated with immaturity), insect damage, mould, discolouration, rancidity and a discoloured crest associated with germination (Evans and Hofman, 2005). Kernel recovery is a measure of kernel yield and will not be discussed as a quality parameter in this chapter.

Commercial processors also market the macadamia kernel based on appearance, and receive a premium for whole undamaged kernel. Odour, taste and texture are also primary considerations for processors, and nuts showing rancidity, identified by 'off' odours and flavours, are rejected (Evans and Hofman 2005). Texture is determined by the moisture content of the kernel, a factor that depends on appropriate drying and storage. Shelf life, i.e. how long processed kernel can be stored before the onset of rancidity, is another major concern for processors and marketers.

19.3.1 Oil content and immaturity

Oil content is perhaps the most important indicator of quality in macadamia and is measured by the specific gravity of the nuts (Joubert, 1986; Nagao and Hirae, 1992). Nuts with approximately 72% oil content or more float in water and are considered mature, those with less oil than this are considered immature (Joubert, 1986; Nagao and Hirae, 1992). Immature kernels are low in oil, and immaturity is a major cause of reject macadamia kernels. Immature kernel can be caused by early abscission due to a range of preharvest factors, especially pests and diseases.

19.3.2 Quality defects

Processors pay macadamia growers according to the quality of the kernel and calculate payments based on the percentage of nut-in-shell with quality defects. Quality defects, also called unsound kernel, include mould, germination, insect damage, and discolouration (Evans and Hofman 2005). Mould appears as discolouration, often with powdery fruiting bodies and is frequently found when nuts are left on the orchard floor for long periods, or if there is wet weather during harvest. Germination is identified by a green or discoloured crest on the kernel.

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Insect damage may result in a depression or brown or translucent lesion in the kernel, or a chewed appearance of the kernel (Evans and Hofman 2005).

Internal discolouration, also known as brown centres, is a major quality defect. Brown centres are a major cause of kernel rejection in raw kernel when consignments are sent to the processor. This defect can cause a strong off-flavour and odour in the kernel which makes the kernel unmarketable (Le Lagadec 2009). After-roast darkening is a similar defect to brown centres, but it manifests on the surface of the kernel or internally only after roasting (Albertson *et al.*, 2006). It is unclear whether the two defects are related. Other discolouration such as a brown or black appearance of the suture line, the line between the two cotyledons, is related to cultivar.

19.3.3 Appearance

The appearance of macadamia kernels also dictates the return to the processor. Styles vary from processor to processor, but premium styles are generally whole kernel that is free of shoulder damage, dust, discolouration or any defect (O'Hare *et al.*, 2000). Styles of less commercial value include imperfect wholes, pieces and chips. These styles may be used as a snack food, as a cooking ingredient or to produce macadamia oil.

The macadamia embryo (kernel) consists of two large cotyledons and these may separate during postharvest handling and processing. Whole kernel refers to the number or weight of kernels which remain whole during handling. Cotyledon separation results in the problem of reduced whole kernel recovery and results in commercial losses for the processor (Walton and Wallace, 2005a).

Shoulder damage is a term used to describe torn areas on the micropylar hemisphere of the kernel which are thought to be caused by tissue adhering to the shell inner surface (Plate XXXIV). Drying causes shrinkage of the kernel, leaving an air gap around the kernel. This is considered desirable, as it leaves room for deformation of the shell during cracking with minimal kernel damage (Cavaletto, 1983). Some macadamia kernels adhere strongly to the white, enamelled region of the shell (Hartung and Storey, 1939). Shoulder damage occurs when the attached kernel tears away during postharvest procedures, leaving a lesion. Shoulder damage is proof of tissue damage and cell damage. It also involves economic loss in two possible ways: (1) total loss as tissue adhering to the shell and discarded with the shell (Liang, 1977), or (2) reduction in value when torn sections separate from the shell and contribute to pieces. It may also have less obvious economic consequences by causing buyer resistance to a less visually attractive product, and as a site for possible lipid oxidation.

19.3.4 Rancidity and shelf life

Rancidity is one of the most important quality parameters for nuts. The term rancidity refers to 'off' odours and flavours resulting from lipid oxidation or lipolysis (breakdown of oils chemically or by lipase into constituent fatty acids)

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(Pike, 1998). Conditions prior to harvest, during drying and during storage can induce such chemical changes in macadamia kernels (Mason *et al.*, 1995; Kaijser *et al.*, 2000). The high oil content of macadamia makes them prone to rancidity, while the sugar and protein content makes excessive browning of roasted kernels possible if drying and roasting methods are not appropriate (Prichavudhi and Yamamoto, 1965; De la Cruz *et al.*, 1966). Subjective detection of rancid off-flavours by tasting is still used to determine nut quality (Fourie and Basson, 1989), and remains the ultimate measure of rancidity. There are two important pathways leading to rancidity: oxidation and hydrolysis (Robards *et al.*, 1988).

Oxidation leads to oxidative rancidity and is the result of oxygen attacking glycerides. Oxidation can be initiated by heat, pro-oxidants, certain enzymes (lipoxygenases) or light (Robards *et al.*, 1988). Macadamias are usually tested for oxidative rancidity by the Peroxide Value (PV) method (AOAC method 965.33). This test is useful, providing warning of impending flavour deterioration, but is of low specificity (Nawar, 1996; Robards *et al.*, 1988). Oxidation of oils containing linolenic acid produces objectionable flavours, a process which is known as flavour reversion. Macadamia oil typically contains from 0.7% to 2% linolenic acid (McConachie, 1997; Himstedt, 2002), making some flavour reversion possible in macadamia products. New Zealand macadamia oils were found to have Rancimat induction times of 39 h at the standard 110°C, (Kaijser *et al.*, 2000). Thus macadamia oil is relatively stable in oxidation terms and does not readily become rancid. However, conditions for nuts during storage are critical in preventing rancidity. Macadamia kernels rapidly develop rancidity when stored at room temperature at higher moisture content (Cavaletto *et al.*, 1966; Himstedt, 2002). The moisture content was found to be the most important factor influencing the onset of rancidity in raw macadamia kernel (Cavaletto *et al.*, 1966) and roasted kernel (De la Cruz *et al.*, 1966). Kernel moisture content of 1.2–1.6% (dry basis), corresponding to a_w of 0.36–0.44 provides optimum oxidative stability (Dominguez *et al.*, 2007). Nuts should be dried as rapidly as possible after harvest to minimize oxidative rancidity.

Hydrolysis is the consequence of lipolysis (by lipase) or hydrothermal activity and results in release of free fatty acids (FFA), leading to hydrolytic rancidity (Robards *et al.*, 1988). FFA is a measurement of hydrolytic activity in a fat (AOAC method 940.28). Measures of fat acidity normally reflect the amount of fatty acids hydrolyzed from triacylglycerols. FFA is expressed as a percentage by weight of a specified fatty acid, e.g., percent oleic acid (Pike, 1998). Lipolysis in macadamia appears to be related to storage at excessively high temperatures rather than as a result of moulds (Cavaletto, 1983). In macadamias, even small differences in FFA values were highly correlated with differences in flavour scores (De la Cruz *et al.*, 1966). Lipases hydrolyze only emulsified acyl lipids and are active only on the water/lipid interface (Belitz *et al.*, 2004), mandating low moisture content for storage of macadamia kernels (Cavaletto *et al.*, 1966; De la Cruz *et al.*, 1966). Macadamia kernels should be stored at low moisture content (1.5% wet basis) and relatively low temperatures. Some processors are now storing kernels under cold-room conditions.

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The Australian Macadamia Society (AMS) considers 0.2 to 0.6% FFA acceptable (McConachie, 1996). However, there is another recommendation that FFA should be no more than 0.3% (McConachie, 1996). More precise profiling of the fatty acids could be provided by gas chromatography, which yields a more useful measure of hydrolysis (Belitz *et al.*, 2004). The present reliance in the macadamia industry on PV and FFA analysis as indicators of rancidity of macadamias has been described as unreliable, with sensory evaluation the only reliable test (Mason *et al.*, 1998). However, a correlation of chemical tests with instrumental methods may provide a more reliable prediction of rancidity (Fard *et al.*, 2003). The principal volatile components of roasted macadamias that are major determinants of flavour can be identified on the basis of their gas chromatograph (GC) indices and mass spectra (MS) (Crain and Tang, 1975). GC can also be used to detect volatile aldehydes which are in large part responsible for the unpleasant oxidised flavour of lipids (de Man, 1990). Of the various compounds formed during oxidation of lipids, hexanal is one of the most common, and GC measurement of headspace hexanal is one of the methods of determining the extent of oxidation (Pike, 1998). Hexanal has been identified as a volatile rancidity by-product of macadamias and has potential to be an objective chemical measure of rancidity (Himstedt, 2002). Finding ways to prevent rancidity and prolong shelf life in stored macadamia is a major challenge for the macadamia industry to address.

19.3.5 The importance of antioxidants

Antioxidants are considered by biochemists and clinicians as substances that can protect the living tissues against damage by reactive oxygen species (ROS) (Wanasundara *et al.*, 1997). However, the action of antioxidants is not permanent as they delay oxidation without preventing it altogether (Robards *et al.*, 1988). It is important to understand that antioxidants capable of delaying the onset of oxidative rancidity will have no effect on FFA formation due to chemical hydrolysis (Robards *et al.*, 1988). Free radicals and ROS are key chemical species that contribute to changes in food quality and development of disease (Wanasundara *et al.*, 1997). Oxidation of unsaturated lipids is a major cause of food quality deterioration (Wanasundara *et al.*, 1997). Many oils and lipid-bearing foods have been investigated in relation to the content of antioxidants and effect of processing on the antioxidants. However, the factors that determine the oxidative stability of macadamia kernels are largely unknown (Quinn and Tang, 1996). Several phenolic compounds known for antioxidant properties have been identified at very low concentrations (0.004%) in macadamia oil. However, possible synergistic effects of these low concentrations or the effect of other unidentified compounds are not known (Quinn and Tang, 1996). Kaijser *et al.* (2000) also identified the phenolic compounds α-tocopherol and δ-tocopherol in New Zealand cultivars of macadamia at slightly higher levels than Quinn and Tang (1996). Another compound identified was α-tocotrienol and it is possible that the total of tocopherols and tocotrienols may contribute to oxidative stability (Kaijser *et al.*, 2000).

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19.4 Preharvest factors affecting nut quality

19.4.1 Cultivar and site

Cultivar and site can be an important determinant of quality of macadamia. Cultivar can influence all aspects of appearance, flavour and texture. For example, whole kernel is strongly related to cultivar (Wallace *et al.*, 2001; Wallace and Walton, 2005; Walton and Wallace, 2005a). Adhesion of the kernel to the white enamelled interior of the shell has been suggested as a factor in shoulder damage, and this may be related to cultivar (Hartung and Storey, 1939; Wallace and Walton, 2005). Lipids, fatty acid profiles, sucrose concentration and tocopherol content can vary between cultivars, and this can affect oxidative stability (Kaijser *et al.*, 2000; Wall and Gentry, 2007). Site factors such as soil type, drainage, aspect and frost, can also influence quality. For example, the same cultivars can have variable total oil content depending on regions (Table 19.1). The percentage of whole kernels, sugar content, moisture content and total oil content of macadamia cultivars can vary greatly between regions (Kaijser *et al.*, 2000; Wallace and Walton, 2005; Wall and Gentry 2007).

19.4.2 Crop management

Optimal nutrition is essential to maintain quality. Essential categories to consider are soil ameliorants, nitrogen (N), phosphorus (P), potassium (K) and trace elements (Nagao and Hirae, 1992). For N, small but frequent applications are recommended (Stephenson and Gallagher, 1989). Optimum yields and quality are obtained at lower rates than are currently applied (Stephenson *et al.*, 2000). For example, the percentage of first grade kernels is negatively correlated with the rate of nitrogen (Stephenson *et al.*, 2000, 2002). Unsound kernels, including immature, deformed, mouldy and insect-damaged kernels, are lowest at low rates of nitrogen and highest during wet harvest seasons (Stephenson *et al.*, 2000). Lime is indicated as an amendment with repeated N applications to maintain quality (Stephenson *et al.*, 2002). Irrigation and orchard canopy management

Table 19.1 Cultivar differences for oil content of macadamia in different regions of Eastern Australia

Cultivar	Region	Oil content (%)	Author
HAES 344	Lismore	74.89	Himstedt (2002)
	Victoria Park	77.5	Trueman *et al.* (2000)
	Gympie	76.69	Himstedt (2002)
	Bundaberg	76.45	Himstedt (2002)
	Winfield	78.5	Trueman *et al.* (2000)
HAES 741	Winfield	80.5	Trueman *et al.* (2000)
	Victoria Park	77.0	
HV A16	Winfield	81.5	Trueman *et al.* (2000)
HAES 246	Victoria Park	78.5	Trueman *et al.* (2000)

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have been the subject of recent research, but there is no evidence to date that these management practices influence macadamia quality (Trochoulias and Johns, 1992; McFadyen *et al.*, 2005).

19.4.3 Pests and disease

Pests and diseases of macadamia can cause damage to all parts of the macadamia tree, loss of nuts and reductions in quality (Nagao and Hirae, 1992). Pests and disease will be discussed mainly for their impacts on quality, and in particular, immature kernel.

Insect pests are a major cause of immature and reject kernel in macadamia. Fruit spotting bug (*Amblypelta nitida*) and banana spotting bug (*A. lutescens*) are sucking bugs that inflict major damage on a range of horticultural crops including macadamia. Premature abscission of nuts is one of the effects of fruit spotting bug feeding and fruit spotting bug thus contributes to immature kernel. Fruit spotting bug can also damage mature kernel, leaving a brown lesion, causing rejection at the processors (Evans and Hofman, 2005). In Australia, the macadamia nut borer, *Cryptophlebia ombrodelta* and in Hawaii the Koa seedworm, *C. illepida* can also cause premature nut drop (Ironside, 1981; Nagao and Hirae, 1992). Damage by macadamia nut borer and Koa seedworm can cause much of the crop to shed before it is fully mature, resulting in higher rejects due to less grade 1 kernel. *Nezara viridula*, the green vegetable bug is also a pest in Hawaii and Australia. Green vegetable bug reduces quality by leaving a discoloured pit on the kernel surface and causes industry-wide damage of up to 3.7% (Golden *et al.* 2006). In some cases outbreaks can cause damage to 25–50% of nuts (Follet *et al.*, 2009). The macadamia shothole borer (*Hypothenemus obscurus*) also causes damage to mature and fallen nuts and is a major pest in Hawaii (Nagao and Hirae, 1992). Other pests that damage nuts in South Africa include the false codling moth, *Cryptophlebia leucotreta*, the macadamia borer, *C. batrachopa*, the litchi moth, *C. peltastica* and the carob moth, *Ectomyelois ceratoniae* (Nagao and Hirae, 1992). Control is achieved with integrated pest management (IPM) programmes combining monitoring of insect populations with chemical and biological control. IPM programmes are established or under development in Australia, Hawaii and Africa.

Another source of immature kernel in Australia is premature nut drop caused by infection of the husk by husk spot, *Pseudocercospora macadamiae* (Beilharz *et al.*, 2003). Kernel quality is drastically affected by the low oil content of immature kernels (Mayers, 1993; Akinsanmi *et al.*, 2007). Husk spot is currently controlled with carbendazim and copper fungicides, but spraying early, at the match-head phase of nut development, gives the best control (Akinsanmi *et al.*, 2007). Alternative fungicides also show promise (Akinsanmi *et al.*, 2008).

In Hawaii diseases such as *Enterobacter cloacae* are associated with grey kernel, a disease associated with grey colour, off flavour and foul odour (Nishijima *et al.*, 2007). Healthy kernels become contaminated with the odour and entire batches become unmarketable. High levels of moisture are associated with the development of the disease (Nishijima *et al.*, 2007).

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19.5 Quality and the on-farm postharvest chain

19.5.1 Harvest operations

Fruits of macadamia are usually harvested from the orchard floor following natural abscission (Mason, 2000). Abscission can occur over several months within a cultivar and varies in timing between cultivars (Trueman *et al.*, 2000). Ethephon has been widely used to induce abscission in macadamia and does not affect kernel oil content or quality (Trueman *et al.*, 2002; Trueman, 2003a,b).

Early season harvests often have high levels of immature nuts and other quality problems (O'Hare *et al.*, 2000). Jones (1939) observed that for some trees, oil content of ground-harvested nuts declined and reducing sugars increased just before harvest. This may have been due to the nuts beginning germination while on the ground (Jones, 1939). It is even possible for nuts to begin to germinate on the tree (Jones, 1939). Careful planning of harvest frequency is essential to ensure optimum quality of nuts is achieved (Liang *et al.*, 1996). Harvest intervals of 3 weeks or less are recommended, especially during rainy weather, to avoid kernel deterioration due to germination, fungal growth or exposure to sunlight (Mason and Wells, 1984; Nagao and Hirae, 1992; Liang *et al.*, 1996, Walton and Wallace, 2009). Most macadamia orchards have plantings of more than one cultivar, so that harvesting extends over several months and often involves multiple harvest rounds over the same rows.

Delaying harvest is known to reduce quality of macadamia kernel. Delaying harvest for 3–5 weeks reduces whole kernel and increases shoulder damage (Walton and Wallace, 2009). After-roast darkening is also increased by delaying harvest (Walton and Wallace, 2009). In particular, nuts left in the sun for 1 month show discolouration and poor flavour scores (Mason and Wells, 1984). Harvest intervals of less than 3 weeks are recommended for best kernel quality.

19.5.2 Dehuskers and macadamia quality

The first step in processing macadamia nut after harvest is the removal of husk (pericarp), normally accomplished on-farm by mechanical dehuskers. The fibrous husk of the macadamia fruit makes up as much as 40–45% of the fruit weight (Cavaletto, 1983). Industry recommendations are to dehusk macadamias within 24 hours of harvest to avoid heat accumulation due to respiration (Cavaletto, 1983). Macadamia nut dehuskers use various methods to fracture and remove the husk, such as impact by a blade, a rubbing action between two rough surfaces such as a rubber sheet and steel spiral roller, and passing between a spiral roller and circular blades (Luan and Liang, 1983). Nuts usually fall from the tree at around 25% moisture content (Weinert, 1993), and at dehusking are typically at 20–23% moisture content (Wallace and Walton, 2005; Walton and Wallace, 2009).

Dehusking machines have the potential to cause loss of quality. Dehusking at field moisture content with two mechanical dehuskers causes a significant increase in shoulder damage (Walton and Wallace, 2005b). In addition, dehusking at lower moisture content (around 10%) results in significant loss of whole kernel

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(Wallace and Walton, 2005). Careful adjustment of dehusking machines is important to minimize damage.

19.5.3 Sorting and resorting

Following dehusking, nuts must be carefully inspected to remove foreign matter and unsound nuts. Thorough on-farm sorting is essential to remove small, damaged and unsound kernels very early in the postharvest chain. Size is very important as nuts smaller than 18 mm are more likely to be immature (Bungay, 2003). Relying on visual belt sorting alone may result in many unsound kernels, including mouldy product, passing into the processing line. More objective systems based on specific gravity such as water and air sorting are most practical and cost-effective. Some producers use water flotation on-farm to remove immature nuts. This is a very cost-effective process for the industry as it is very inefficient to handle and transport nuts to a processor only to have the kernels rejected in the factory for immaturity and quality defects.

19.6 Drying effects on quality

Drying is one of the most important steps in the macadamia processing chain for determining the quality. Drying determines storability, palatibility and roasting qualities of kernels (Cavaletto, 1983). Correct moisture content is important for food products for microbial stability, texture and product quality (Labuza and Contreras-Medellin, 1981; Kowitz and Mason, 2001). Moisture content in macadamia may be expressed either as a wet-basis (w.b.), commonly used by industry, or as a dry-basis (d.b.), commonly used in scientific publications (Kowitz and Mason, 2001).

Water is present in two forms: (1) bound water, which is held by strong chemical forces with other constituents and is unchanged by processes such as drying and (2) free water, the balance of water within the nut, including both adsorbed and absorbed water (Coultate, 2002). Free water is readily removed by the drying process, while bound water can only be removed by high temperatures. High temperatures also induce chemical changes and loss of quality (Mason *et al.*, 1998). The term water activity (a_w) refers to how much unbound water is present in the food. Water activity is an index and the scale extends from 0.0, where no water is present at all (either bound or unbound), to 1.0, equal to pure water. Water activity a_w increases with equilibrium relative humidity (ERH), and ERH for a given a_w can be readily calculated, e.g., at a_w of 0.3 for macadamia ERH will be 30% (Beuchat, 1978).

There is an optimum a_w at which a dry food has the longest shelf life, close to the monolayer moisture level, usually around 0.2 to 0.3 for most foods (Labuza and Contreras-Medellin, 1981; Coultate, 2002). This is the point where all free water has been removed and only bound water remains (Coultate, 2002). The functional connection between moisture content and ERH is expressed as

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experimentally determined sorption isotherms (Acker, 1962; Kowitz and Mason, 2001). Sorption isotherms have been determined for macadamia nut in shell and kernels and are critical for storage (Palipane and Driscoll 1993, 1994; Dominguez *et al.* 2007). There can be a large difference between the sorption isotherms for roasted nuts and raw nuts, with the former showing a reduced capacity for water adsorption. This is attributed to a decrease in the available sites in the substrate for water adsorption due to chemical changes induced by roasting (Martinez-Navarrete and Chiralt, 1996).

Dried macadamia nuts will rehydrate at elevated RH. The moisture content during storage in a closed system will equilibrate depending on temperature and RH (Kowitz and Mason, 2001). Water adsorption isotherms on rehydration differ from those for desorption, a phenomenon known as hysteresis (Acker, 1962; Palipane and Driscoll, 1993, 1994). Macadamia kernels with a moisture content of 1.5% (w.b.) have water activity of approximately 0.3 (Beuchat, 1978; Dominguez *et al.*, 2007). Because of this, dry kernels (e.g., 1.5% w.b.) must be protected from moisture because exposure to RH greater than 30% will result in moisture gain (Cavaletto, 1983).

19.6.1 Drying methods for macadamias

At harvest, macadamia nut-in-shell can have a moisture content as high as 30%, and it is essential to reduce this to below 10% to reduce hydrolytic activity and prevent microbial growth (Mason, 2000; Kowitz and Mason, 2001). Moisture content is a critical factor influencing macadamia stability (Cavaletto *et al.*, 1966). However, drying must be accomplished in ways that do not compromise other quality parameters. The aim must be to have a drying regime that permits the highest moisture removal rate and energy efficiency within operational restraints, including quality of product (Kowitz and Mason, 2001; Silva *et al.*, 2006; Borompichaichartkul *et al.*, 2009). Nut-in-shell is generally dried in stages. The first stage reduces moisture content to less than 10% (w.b.) and is often carried out on farms, in silos or drying bins (Kowitz and Mason, 2001; Silva *et al.*, 2006). The second stage dries nut-in-shell to less than 3.5% M.C. (w.b.) using heat, and may occur at a processing factory or centralized facility (Silva *et al.*, 2006).

Macadamia nuts dried to around 3.5% nut-in-shell moisture content (w.b.) before cracking have a kernel moisture content of around 1.5% (w.b.). This renders the shell brittle and easy to crack, but unfortunately also predisposes the kernel to shattering (Tang *et al.*, 1982). Drying high moisture macadamia nut-in-shell rapidly, for example at 50°C, causes the kernel to become extremely brittle and susceptible to physical damage such as chipping and breakage (Tang *et al.*, 1982). Drying nuts too quickly can also cause loss of the characteristic macadamia flavour (Tang *et al.*, 1982).

Drying nuts too slowly can cause additional problems such as mould, germination and browning of the centre of the kernel. Brown centres are a major quality defect and a leading cause of rejection by processors, costing the Australian industry alone around $2 million per annum (Le Lagadec, 2009). Brown centres

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are related to incorrect nut-in-shell drying regimes and storage of wet nuts in poorly ventilated silos, and may be exacerbated by wet conditions during harvest (Kowitz and Mason, 2001; Le Lagadec, 2009).

Temperature during both phases of drying is an important factor in drying time and quality of the dried product. There are several suggested drying regimes for macadamias (Table 19.2). One current recommended practice for drying macadamias is an incremental process, 2 days at 38°C, 2 days at 45°C, and 2 days at 60°C (Anon., 2002). This is a variation of a method developed by Prichavudhi and Yamamoto (1965), who used higher temperatures. In the first phase of drying, current recommendations are that the drying temperatures should never exceed 30°C when nut-in-shell is above 15% moisture content to prevent: (1) over-drying of nut-in-shell at the bottom of the drying vessel closest to the air source, (2) kernel becoming brittle from drying too rapidly (Prichavudhi and Yamamoto, 1965; Kowitz and Mason, 2001). The second phase of drying often occurs at the processor and many of the details of their drying methods are kept confidential by processors (Grimwood, 1971; Weinert, 1993).

Design of appropriate drying systems for macadamia is an ongoing research issue, and a major issue for the industry. During the first stage of drying, existing systems may use silos with ambient or heated air drying, boxes, trays or a Bungay bin system (Bungay, 2003; Silva *et al.*, 2006). Using air for drying with a relative humidity of 60% or more results in macadamias rewetting (Moltzau and Ripperton, 1939). For maximum efficiency and quality of nuts, the air used for drying needs to be lower in relative humidity than the nut bed, or nuts will not dry, and will even rewet if the relative humidity of air used is higher than in the nut bed. This is best achieved with a combination of supplementary heating or dehumidified technology and a relative humidity based aeration controller (Kowitz and Mason, 2001). Many current systems used in the industry are based on silos designed for grains and use only ambient air to control the humidity of the nuts (Quinlan *et al.*, 2008).

The disadvantages of existing drying systems are that they are time consuming and energy expensive (Silva *et al.*, 2006). Experimental methods for drying include microwave drying (Silva *et al.*, 2006) and hybrid drying systems employing heat pump drying and hot air drying (Borompichaichartkul *et al.*, 2009). These show promise as new methods to reduce drying time and cost.

Table 19.2 Drying regimes for macadamia nut-in-shell

Stage 1	Stage 2	Stage 3	Stage 4	Reference
4-5d @ ambient	2–3d @ 38°C	4–5d @ 50°C	1–2d @ 60°C	Cavaletto, 1983
2d @ 38°C	2d @ 45°C	2d @ 60°C	----	Anon., 2002
3–4d @ 30°C	2–3d @ 40°C	X d @ 50°C[a]	----	Mason *et al.*, 1995
6 d @ 45°C				Trueman, 2003a

Note: a Dried at 50°C until kernel MC of 1.0–1.5% achieved.

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19.7 Handling and physical damage to macadamia

Between harvest and cracking, nut-in-shell is subjected to many physical stresses. These include elevation and drops into containers and conveyors for harvesting, drying, transport and processing. While the Industry Code of Sound Practice recommends that drop heights be no more than 2 metres (O'Hare *et al.*, 2000), that height is often exceeded and drops of 4 to 5 metres into silos and trucks are common. In addition, repeated drops from a moderate height such as 2m cause damage. Quality of macadamias can be reduced in a number of ways, e.g., shoulder damage, production of pieces, oiliness and dustiness, and bruising which results in after-roast darkening of kernel (Walton and Wallace, 2008, 2010). Frequent 2 metre drops of macadamia nut-in-shell at low moisture content (3% w.b.) are especially damaging, causing shoulder damage, oiliness and dustiness of the kernel. Dropped nuts have an abraded cuticle and an oily appearance, an indication of cell membrane damage (Walton and Wallace, 2008). This damage is most likely to occur at the processor after drying of nut-in-shell. Surprisingly, percentage of whole kernel is not reduced by dropping and is strongly related to the cultivar of the nut (Wallace *et al.*, 2001; Walton and Wallace, 2005a; Walton and Wallace, 2008). There is also some evidence that different cultivars vary in susceptibility to damage (Wallace and Walton, 2005).

Rough handling can cause damage to macadamia kernels even at the early stages of postharvest processing. Nut-in-shell are at high moisture content for most of the handling operations on the farm and are subject to frequent drops of various heights. Frequent drops of nut-in-shell at intermediate (10%) and high (20%) moisture content (w.b.) cause damage. Nut-in-shell dropped at 20% moisture content produces kernels with after-roast darkening at roasting (Wallace and Walton, 2005). Nuts dropped at 20% moisture content show little evidence of damage until they are roasted (Wallace and Walton, 2005). Impacts can be reduced by installing 'easy let-downs' in macadamia silos on-farm, design features which allow nuts to roll down a series of ramps or drop in stages rather than just in a single drop (Bungay, 2003). Another impact-reducing technology is special tough, resilient polymer surface coatings now available. These surfaces can be applied to all processing equipment and have potential to reduce impacts to nut-in-shell, as well as reduce wear and tear on equipment and reduce the high noise levels associated with macadamia processing.

19.8 Factory processing of macadamia

19.8.1 Cracking

The shell of macadamia is a cellular solid with low density and high strength, and is similar to woods (Chun-Hui and Yiu-Wing, 1994/1995). In contrast to woods, the macadamia nut shell is isotropic and uniform, whereas the woods are highly anisotropic (Chun-Hui and Yiu-Wing, 1994/1995). The cells in woods can be considered two-dimensional, with cells elongated parallel to the trunk, and

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greatest strength in the axial direction. In macadamia shell, the cells are three-dimensional, and have random orientation (Chun-Hui and Yiu-Wing, 1994/1995). This structure gives macadamia shell impressive properties when compared with man-made materials. Shells have about the same hardness as annealed, commercial purity aluminium, and are stronger in tension than concrete (Jennings and Macmillan, 1986). These testa features help explain a number of important characteristics of macadamia. First, the nuts are very difficult to crack, and extraction of kernels requires considerable force, a risk factor for kernel damage. Second, the testa is an effective protector of the embryo from predation and damage under natural conditions, although insects and rodents may penetrate it at some stages (Jennings and Macmillan, 1986). It is not known if this hard, unyielding testa is a cause of damage to the kernel during impacts.

Macadamia kernels shatter easily at very low moisture contents e.g., 1.5% (w.b.) (Tang *et al.*, 1982), which corresponds to nut-in-shell moisture content of around 3.5% (w.b.). This has implications for nuts in the factory as for ease of cracking, shells need to be at low moisture content (Liang *et al.*, 1984). Cracking at 3.5% nut-in-shell moisture content (w.b.), corresponding to 1.5% kernel moisture content (w.b.), is recommended because that facilitates shell fracture and thus reduces the risk of physical damage to the kernel (Mason *et al.*, 1998). However, cracking nuts at very low shell moisture content reduces kernel quality expressed either in wholes and halves or in smaller grades of nuts (Liang, 1977). Best recovery of kernel has been reported at a moisture content range of 7–12% (w.b.) at cracking (Sarig *et al.*, 1980). More information is needed on the relationship between macadamia shell and kernel moisture content at cracking. In macadamia, nuts with high moisture content (3.28% d.b.) can withstand greater deformation without failure of the kernel (Liang, *et al.*, 1984). Cracking macadamias at 'medium' kernel moisture content (2.3–4% w.b.) produces higher quality in terms of higher whole kernel and less size reduction of kernels than at 1% (w.b.), a common figure for processed kernel (Liang, 1977). The best relationship between nut moisture content and kernel quality at cracking (in terms of wholes and halves) was found at 7% to 12% nut-in-shell moisture content (w.b.) (Sarig *et al.*, 1980).

19.8.2 Roasting

Roasting of macadamia commenced in Hawaii (Moltzau and Ripperton, 1939). The fledgling Australian industry at first adopted Hawaiian roasting practice until studies such as those of Leverington and Winterton (1963) and Winterton (1966) modified procedures. Most kernels initially were roasted in oil, but Leverington and Winterton (1963) developed a dry air roasting regime.

There are a number of factors that are known to influence the quality of roasted product, such as temperature and duration of roasting, and moisture content of kernels at roasting. It is essential that kernels are below 1.5% moisture content (w.b.) at roasting to avoid excessive browning (Prichavudhi and Yamamoto, 1965), further, De la Cruz *et al.* (1966) state that kernels should be at no more than

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1.1% moisture content (w.b.) at roasting for maximum sensory and chemical quality. Moisture content at the time of roasting is also important in determining the final colour. Kernels with moisture content higher than 2% (w.b.) do not have crisp texture, brown too rapidly and do not have good shelf life (Cavaletto, 1983). Kernels should also be of high oil content, as indicated by specific gravity of less than one, as there is an inverse relationship between oil content and sugar content. High reducing sugar content leads to dark kernels at roasting (Cavaletto, 1983; Albertson *et al.*, 2005).

The time/temperature relationship at roasting is proposed as the most important factor in the prevention of rancidity in roasted nuts (Leverington, 1962). Too high a temperature will not cook the kernels through to the centre by the time a desirable colour is obtained (Leverington, 1962). When this happens, the binding sites for water in the centre of the kernels are not reduced effectively by roasting (Martinez-Navarrete and Chiralt, 1996).

The genotype may also have an influence on the quality of roasted macadamia. Some researchers have recommended that *M. integrifolia* and *M. tetraphylla* kernels should be separated before roasting because of different roasting characteristics and resultant variable quality of roasted product (Grimwood, 1971). Difficulties such as this suggest the desirability of segregating cultivars for roasting, and having defined standards for each cultivar. There is also a need for flexibility when roasting, and varying time of roasting as necessary to achieve the desired colour.

Most roasted macadamias in Hawaii were roasted in oil (Grimwood, 1971). One problem with oil roasting can be that degradation of roasting oil due to heating can lead to peroxidant contamination of kernels (Winterton, 1966; Grimwood, 1971). This can be counteracted to some extent by treating roasted kernels with antioxidants (Cavaletto and Yamamoto, 1971). This practice was not considered necessary for kernels roasted correctly (Winterton, 1966). Another problem with oil roasting is that kernels can lose substantial quantities of endogenous oils to the frying oil (Cavaletto and Yamamoto, 1971). However, an advantage of oil roasting is that a more even colour of product is obtained (Grimwood, 1971). Various methods have been reported for oil roasting macadamias (Table 19.3). When oil roasting, temperatures between 115°C and 125°C achieve better control of colour–time relationships than at 135°C (Mason *et al.*, 1995). Roasting at 135°C produced inferior flavour compared with roasting at 115 to 125°C (Mason *et al.*, 1995).

Most roasted macadamias produced in Australia are air-roasted. Various air-roasting regimes have been reported for roasting macadamia kernel in air (Table 19.4). Macadamia processors in Australia tend to use low temperatures when roasting to minimize the risk of dark kernels, considered to be partly due to kernels of mixed cultivars. The roasting regimes presented in Table 19.3 and Table 19.4 were those used by experimenters under laboratory conditions. For processors, batch sizes and the scale of roasting equipment are very different, and equipment used also varies. An example of dry roasting methods used by a processor is presented in Table 19.5.

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Table 19.3 Roasting regimes for roasting macadamias in vegetable oils

Cultivar or species	Oil type	Temperature (°C)	Duration (min)	Author
M. integrifolia	Unknown	127	25	Winterton, 1966
HAES 246	Coconut	127	15	Cavaletto and Yamamoto, 1971
M. integrifolia	Coconut	135 127	12–15 12	Grimwood, 1971
HAES 508	Coconut	127	15	Prichavudhi and Yamamoto, 1965
Hybrids♦	Coconut	127	12	Lemmer *et al.*, 1998
HAES 246, HAES 508	Coconut	115 125 135	19–35 # 10–14 # 4 #	Mason *et al.*, 1995

Notes: # To desired colour standard ♦ Nelmak 1, Nelmak 2, Nelmak 26, Beaumont (695)

Table 19.4 Roasting regimes for roasting macadamias in air

In-shell or shelled	Cultivar or species	Temperature (°C)	Duration (min)	Author
Shelled	*M. integrifolia* *M. tetraphylla*	135 127	25	Leverington and Winterton, 1963
Shelled	*M. integrifolia* *M. tetraphylla*	163–190	12–15	Grimwood, 1971
In-shell	Yonik	110	60–75	Rosenthal *et al.*, 1984
In-shell	Beaumont (695)	102	70–75	Basker and Kadman, 1986
Shelled	Hybrids* 791, 741, 788, 508, 246	127 127	12 25	Lemmer *et al.*, 1998

Note: * Nelmak 1, Nelmak 2, Nelmak 26, Beaumont (695)

19.8.3 After-roast darkening

After-roast darkening is a quality defect of macadamia that only manifests when kernel are roasted. The darkening is associated with membrane damage, due to bruising or exposure to moisture and high temperatures (Albertson *et al.*, 2005; Walton and Wallace, 2010).

Kernel susceptible to after-roast darkening shows increased concentrations of reducing sugars (glucose and fructose), and lower concentrations of sucrose

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Table 19.5 Example of a roasting regime for a batch roaster used by an anonymous commercial macadamia processor

Roast colour	Nut style	Temperature (°C)	Duration (min)
Light	Large, style 0–4	125	26
	Small, 5 – fine	130	40
Medium	Large, style 0–4	130	50 (25×2)*
	Small, 5 – fine	135	50 (25×2)*
Dark	Small, 5 – fine#	138	40

Notes: * Trays mixed after 25 min
Roasted for biscuits, confectionery

(Albertson *et al.*, 2005; Wall and Gentry, 2007). The cell wall of macadamia kernel contains invertase, an enzyme that cleaves sucrose into glucose and fructose, and invertase exposed by cell wall damage is thought to play a key role in after-roast darkening reactions of macadamia (Albertson *et al.*, 2006).

19.9 Conclusions

Maintaining quality is a major challenge for the macadamia industry worldwide, and quality is a strong driver of commercial returns to both growers and processors. Quality kernel of macadamia are defined as having 72% or above oil content, whole or half kernel free of defects such as browning and insect damage, and with a pleasant odour, taste and texture.

Both preharvest and postharvest practices can impact on macadamia quality. The ultimate quality of the crops is determined by preharvest factors including cultivar, site, pest and disease management, and nutrition. Careful selection of cultivars and sites and improved management of pests and diseases can greatly improve quality parameters such as oil content and appearance. Postharvest processes can only preserve quality, they cannot improve quality once the crop has been harvested. Quality can be preserved on the farm with postharvest systems that incorporate frequent harvesting, careful adjustment of dehusking equipment, efficient drying systems, and gentle handling to prevent damage. Quality at the processing factory is also dependent on efficient drying systems, gentle handling, effective cracking and appropriate roasting regimes.

Macadamia has made substantial inroads as a world industry and continues to grow and benefit from strong research programmes on selection, breeding, physiology, fruit production and postharvest processing. There are some knowledge gaps in understanding the processes that lead to whole kernel and the causes of quality defects such as discolouration, brown centres, and after roast darkening. A major knowledge gap is the preharvest and postharvest influences on shelf life and rancidity. A key challenge for the industry is to encourage the adoption of the research and ensure best practices such as frequent harvests,

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efficient drying systems, and gentle methods of postharvest handling are standard across the macadamia industry.

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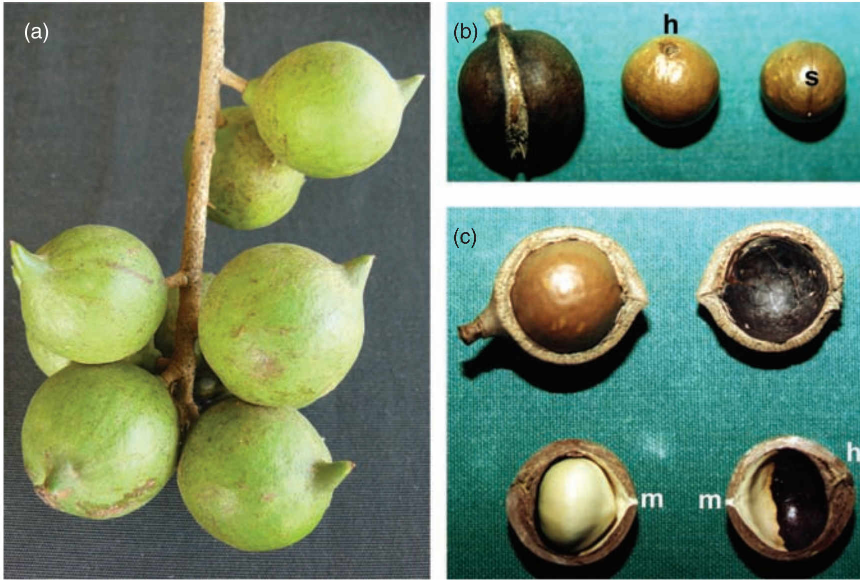

Plate XXXIII (Chapter 19) Mature *Macadamia* fruit morphology. (a) raceme of *Macadamia* fruit showing green pericarp. (b) Left to right: dehiscent fruit; seed ('nut'), h, hilum; m, seed micropyle (white dot at bottom of seed); s, suture between hilum and micropyle. (c) Clockwise: seed in pericarp ('husk'); pericarp interior with tannin coated endocarp; open testa ('shell') showing enamel layer on inner surface of testa, m, micropyle at enamel end; h, hilum at opposite end; embryo in position in testa with cotyledon apex extending towards micropyle (m).

Plate XXXIV (Chapter 19) Macadamia whole kernels with shoulder damage, visible as damaged areas near the apex of the kernel.

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20

Mamey apple (*Mammea americana* L.)

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Abstract: Mamey apple is mainly eaten raw in fruit salads or made into jellies or ice cream. The fruit is highly perishable which limits its shelf life and transport. The use of low temperatures for its handling and storage is limited because the fruit is sensitive to chilling injury. Therefore, other preservation techniques may represent better options. Very little research has been done on the postharvest physiology and handling of the fruit. Controlled and/or modified atmospheres may be required in order to extend its storage life. In fact, more research on mamey apple is needed in almost all aspects of postharvest physiology and technology. A recent scientific study has found mamey apple to have protective effects on gastric ulcers, using an animal model. Further research on its health benefits would also be beneficial.

Key words: *Mammea americana*, postharvest, physiology health benefits.

20.1 Introduction

Mamey apple (*Mammea americana*) is an appetizing fruit that is little known outside its area of origin. Its high respiration rate makes it highly perishable which limits its shelf life (Yahia, 2004). Some health benefits have been associated with this fruit, although more scientific research is needed to confirm these. The lack of information on mamey apple postharvest physiology and technology limits the preservation techniques that can be used to conserve its quality during storage and shipping (Yahia, 2004).

20.1.1 Origin, botany, morphology and structure

Mamey apple is a tropical fruit that has received little attention from researchers or the fruit trade. Botanically identified as *Mammea americana*, it belongs to the Guttiferae family and it is also known as mammee apple, mammee, St Domingo

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apricot and South America apricot. It is native to the West Indies and northern South America (Morton, 1987). The mamey apple tree is evergreen and reaches a height of 18–21 m. (See Plate XXXV in the colour section between pages 274 and 275.) It has a short trunk with an oval crown. The fruit is about 300 to 500 g in weight. It is a round to oblate fruit, similar in shape and size to an orange (approximately 7.7–9.8 cm in length and 10.9–8.6 cm in diameter). Although mamey apple is commonly thought to be a drupe, it is actually a berry. The rind is russet coloured, covered in brown spots, tough, thick, leathery and wrinkled and about 4 mm in thickness. The fruit contains a large single seed surrounded by a thin layer of yellow flesh. The endocarp, which is also yellow, is about 2–5 mm thick and fused with the testa. When the fruit is fully ripe, the flesh is appetizingly fragrant. Its flavour is similar to that of the apricot, peach or red raspberry, but some varieties are characterized by an acid flavor. Fruit that are too sour or too sweet are considered of low quality (Morton, 1987; Mourao and Beltrati, 2000; Orwa *et al.*, 2009).

20.1.2 Worldwide importance

Mamey apple is commonly grown in the Bahamas and the Greater and Lesser Antilles. It is rarely cultivated in Mexico and Central America but can be found in Costa Rica, El Salvador and Guatemala. Although in some areas the tree is planted for its fruit, other uses include as a wind barrier and as ornamental shade (Morton, 1987).

20.1.3 Culinary uses, nutritional value and health benefits

The fruit is peeled by marking the skin and removing it in strips and the flesh is eaten raw whether it is eaten on its own or as part of a fruit salad. Sometimes it is also served with cream, sugar or wine or used as an ice cream ingredient. Mamey apple is also used to make jam, and when used for this purpose it can be steeped in wine and sugar or left in salted water for a while to remove bitterness. Mamey apple flesh is also used as a filling in pies, tarts and pastes, and frozen flesh is used for sherbets in some areas (Morton, 1987). The high pectin content in ripe mamey apple fruit makes it an optimal ingredient for jelly when combined with fruits like pineapple that have low pectin content and high acidity.

The nutritional value of mamey fruit is presented in Table 20.1. The main sugars are glucose, fructose and sacarose. The fruit is an important source of provitamin A carotenoids (De Rosso and Mercadante, 2007). Total carotenoid content in mamey apple has been reported to be 6.2 mg 100 g^{-1} and vitamin A value to be 688 retinol equivalents (RE) 100 g^{-1} (De Rosso and Mercadante, 2007). Among the carotenoid compounds it contains are 13-*cis*-β-carotene, *trans*-β-carotene, 9-*cis*-β-carotene, *trans*-β-zeacarotene, *trans*-β-apo-10'-carotenal, and *trans*-β-apo-8'-carotenal (Godoy and Rodriguez-Amaya, 1994). Fifty-one volatile compounds responsible for the pleasant flavour in mamey apple have been identified, of which methyl 3-hydroxy-2(S)-methyl propanoate pure enantiomer

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Table 20.1 Nutrient value of mamey apple fruit (per 100 g of fruit fresh weight)

Constituent	Approximate value
Water content	85.5–87.6 %
Calories	44.5–45.3
Protein	0.470–0.088 g
Carbohydrates	11.52–12.67 g
Fat	0.15–0.99 g
Fibre	0.80–1.07 g
Ash	0.17–0.29 g
Calcium	4.0–19.5 mg
Phosphorus	4.0–19.5 mg
Iron	0.15–2.51 mg
Vitamin A	688 RE
Total carotenoids	6.25 mg
13-*cis*-β-carotene	40–60 μg
trans-β-carotene	1000–1820 μg
9-*cis*-β-carotene	10–50 μg
trans-β-zeacarotene	70–90 μg
trans-β-apo-10'-carotenal	360–640 μg
trans-β-apo-8'-carotenal	740–1480 μg
Thiamin	0.017–0.030 mg
Riboflavin	0.025–0.068 mg
Niacin	0.160–0.738 mg
Ascorbic acid	10.2–22.0 mg
Tryptophan	5 mg
Methionine	5–6 mg
Lysine	14–35 mg

Sources: Morton (1987); Godoy and Rodriguez-Amaya (1994); De Rosso and Mercadante (2007)

and 2-methyl butanoic acid are the most significant. Carboxylic acids and C_{13}-norisoprenoids (mainly 2-methyl butanoic acid, 4-hydroxy-β-ion-one and 4-oxo-β-ionol) accounted for the majority of aglycones after hydrolysis of the bound aroma compounds (Morales and Duque, 2002).

The ground seeds of mamey apple have been used as an insecticide and larvidicide for many years (Crombie, 1999) and, without the embryo, they can also be used to make an antihelmintic infusion for adults (Morton, 1987). Liquor is also made from the flowers and taken as a tonic or digestive (Morton, 1987). An infusion of the fresh or dry leaves is believed to help in cases of intermittent fever and extracts of the leaves are effective against *Mycobacterium tuberculosis* (Frame *et al.*, 1998). In addition, antimalarial properties have also been suggested (Brandao *et al.*, 1985).

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The pharmacological properties of mamey apple have been extensively analysed. Ethanol (EtOH) and dichloromethane (DCM) extracts obtained from mamey apple were found to have a protective effect against gastric ulcer induced by HCl/EtOH, using a mouse model. The inhibition of ulcerative lesion index was 54 and 86% for EtOH and DCM extracts, respectively. The same extracts reduced gastric acid secretion, thus increasing gastric pH. This effect is probably due to an induction of endogenous prostaglandins and mucus synthesis (Toma *et al.*, 2005).

Compounds from this fruit called mammein and coumarins have shown anticancer activity (Finnegan *et al.*, 1972). Coumarins isolated from the stem bark of mamey apple also showed cytotoxicity against human epidermoid cancer cell line 9K-B and antimicrobial activity against *Staphylococcus aureus* (Ouahouo *et al.*, 2004). Fifteen isoprenylated coumarins identified in mamey apple have shown strong cytotoxic activity in human colon cancer cell lines HT-29, SW-480, and HCT-116, which appears to be mediated by apoptosis induction (Ouahouo *et al.*, 2004). Out of these, ten coumarins exhibited high antioxidant activity. Higher concentration of mamey apple coumarins has been found in the root as compared to the flesh (Yang *et al.*, 2006). The flavonols catechin and epicatechin have also been identified in mamey apple (Yang *et al.*, 2005).

20.2 Fruit development and postharvest physiology

20.2.1 Fruit growth, development and maturation

Total soluble solids increase during maturation. Acidity is low (0.089–0.091 %) in fully ripe fruit while the sugar content is high (117–128 g kg^{-1}) (Manzano-Mendez and Dris, 2001).

20.2.2 Respiration, ethylene production and ripening

Mamey apple is a climacteric fruit (Yahia, 2004). Its respiration rate at 27°C is 28–40 mg CO_2 kg^{-1} hr^{-1}, and ethylene production rate up to 400 μl kg^{-1} hr^{-1} are among the highest found in fruits (Akamine and Goo, 1978; Yahia, 2004). When harvested at the mature green stage, mamey apple fruit ripens in 3–4 days.

20.3 Maturity and quality components and indices

Mamey apple fruit are commonly harvested at the ripe stage, although, as already mentioned, since they are climacteric, mature green fruit ripen well in 3–4 days after harvest (Morean, 1991). The skin of fully ripe fruit turns slightly yellow. Sometimes this is not apparent and it is necessary to scratch a small portion of the peel with a fingernail. If a green colour is present, the fruit is not ready for harvesting; a yellow colour indicates that the fruit is ready to eat.

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20.4 Postharvest handling factors affecting quality

20.4.1 Temperature management

Mamey apple fruit are sensitive to chilling injury and thus low storage temperatures must be avoided to prevent the development of undesirable flavours and odours, flesh browning and softening (Yahia, 2004). Fruit kept at 27°C for 2 weeks had higher total soluble solids than those kept at 15°C (11.1 and 9.6%, respectively), while pH, total acidity, and sugar concentration did not differ (Manzano-Mendez and Dris, 2001).

20.4.2 Atmosphere

Fruit stored at 27°C or 15°C for 2 weeks under controlled atmosphere (5.1% CO_2, 5.6% O_2, 89.3% N_2), did not differ in their content of total soluble solids (TSS). However, when kept in normal air, fruit at 27°C had higher TSS contents. Temperature of 15°C and controlled atmosphere were reported to delay fruit ripening (Manzano-Mendez and Dris, 2001; Yahia, 1998; 2008).

20.5 Physiological disorders

As already mentioned, mamey apple fruit is sensitive to chilling injury (Yahia, 2004). Chilling injury symptoms include failure to ripen, accelerated softening, development of brown spots in the pulp and development of off-flavours and aromas (Yahia, 2004).

20.6 Pathological disorders

Leaves of the mamey apple tree can be attacked by a black mildew (*Aulographum melioloides*) (Orwa *et al.*, 2009). The tree can be attacked by heart rot, which can enter through basal scars and infect old trees.

20.7 Insect pests

Old trees can be attacked by wet-wood termites (Orwa *et al.*, 2009).

20.8 Postharvest handling practices

20.8.1 Harvest operations

The mamey apple season is from May to July in the Bahamas. However, in Barbados fruits begin to ripen in April, and in Florida they ripen from late June until August. The fruit are harvested by clipping the stem, leaving a small part of the peduncle attached (Morton, 1987).

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20.8.2 Control of ripening and senescence

Ripening of mamey apple can be delayed by storage temperatures of 15 ± 2°C and controlled atmosphere conditions (5.1% CO_2, 5.6% O_2, 89.3% N_2) (Manzano-Mendez and Dris, 2001; Yahia, 1998; 2008).

20.8.3 Recommended storage and shipping conditions

Since the fresh fruit is perishable, it may be more suitable to export the fruit's pulp (rather than the fresh whole fruit). The stability of untreated, sterilized or pasteurized pulp of mamey apple during storage at −30°C for 90 days has been studied. Physicochemical parameters such as pH, °Brix, and acidity were less variable in thermally treated fruit than in untreated fruit. Ascorbic acid degradation was lower in fruit that were pasteurized and thermal treatment also inhibited microbial growth during storage (Cedeño *et al.*, 2010).

20.9 Processing

A patent application filed in 2008 describes effective dehydration methods to obtain stable powders of mamey apple pulp with prolonged shelf life (up to 1 year) at ambient temperature. This powder conserves the original organoleptic properties of fresh mamey fruit according to the inventors. Through this method, the fruit can be preserved for longer periods, as the water loss, enzymatic degradation, decay, and transport and storage problems of the fresh product are avoided. Ascorbic or citric acids are added to the powder (0.01–2%) to preserve the product. The powder can be rehydrated in water, milk, juice, etc., and used in the same way as the fresh pulp, which makes the product very flexible. The production process of mamey apple powder includes selecting the fruit, which are then washed and sanitized. They are then cut and seeded and the pulp is dehydrated by methods such as hot air (60–120°C for 0.5 to 4 h), microwave (60–110°C for 3 to 50 min), or thermal drying using temperatures from 60 to 120°C for 0.5 to 4 h. The skin of mamey apple fruit is separated from the pulp at the end of this first dehydration stage. After that, the pulp is subjected to an additional dehydration step using the same conditions. Dried pulp is ground and citric or ascorbic acids are added. The final product is packed in plastic or glass bottles or polyethylene bags (Jimenez-Mendoza, 2008).

20.10 Conclusions

Mamey apple are mainly eaten raw in fruit salads or made into jellies or ice cream. A recent scientific study has found that mamey apple has protective effects against gastric ulcers, but further research on its health-promoting properties is necessary. The fruit is highly perishable which limits its shelf life and transport. The use of low temperatures when handling the fruit is limited because it is sensitive to

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chilling injury and therefore other preservation techniques may be better options. Very little research has been done on postharvest physiology and handling of the fruit. Controlled and/or modified atmospheres may be required to extend the storage life of this fruit. More research on mamey apple is warranted.

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(a)

(b)

(c)

(d)

Plate XXXV (Chapter 20) (a) Mamey apple tree; (b)–(c) mamey apple fruit; (d) exterior and interior of mamey apple fruit.

(a)

(b)

(c)

Plate XXXVI (Chapter 21) (a)–(c) Mamey sapote fruit.

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21

Mamey sapote (*Pouteria sapota* Jacq. H. E. Moore & Stearn)

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Abstract: Mamey sapote is a climacteric fruit popular in some countries such as Mexico. In addition to being consumed fresh, it is also processed and consumed in different forms, such as in ice creams. This chapter describes the information available on the postharvest physiology, handling and processing of the fruit.

Key words: *Pouteria sapota*, Mamey sapote, postharvest, nutrition, processing.

21.1 Introduction

Mamey sapote fruit (*Pouteria sapota* Jacq. H. E. Moore and Stearn) has received little attention in international markets. This is in spite of its high potential for commercialization in regions where it is considered an exotic fruit, and the high levels of carotenoids in its pulp, which make it attractive, nutritionally speaking. The trees of *P. sapota*, native to Mexico and Central America, are found in the wild and are sometimes cultivated for the fruit. However, the fruit's climacteric behaviour makes it highly perishable and thus postharvest handling activities need to be targeted at maintaining its quality while extending its shelf life (Yahia, 2004).

21.1.1 Origin, botany, morphology and structure

The mamey sapote is also called by the common names sapote, zapote, mamey, mamey colorado, sapote mamey, chico-mamey, marmalade-fruit, marmalade-plum and grosse sapote. Its Latin name is *Pouteria sapota* Jacq., H.E. Moore and Stearn, synonyms *Colocarpum sapota* (Jacq.), Merr., *Calocarpum mammosum*, Pierre., *Achras mammosa* L., *Lucuma mammosa*, Gaertn., *Vitellaria mammosa*,

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Radlk., and *Achradelpha mammosa*, Cook. It is native to the south of Mexico (as far south as the Yucatan Peninsula), Guatemala, Belize, the north of Honduras and the Atlantic coast of Nicaragua (Azurdia, 2006).

Pouteria sapota is an evergreen tree that can grow up to 12.2 m and in more tropical areas can reach more than 18.3 m. It has a thick trunk and narrow or spreading crown and presents white latex. The leaves grow in clusters at the tip of the branches and are pointed at both ends with a length up to 30 cm and 10 cm wide. *Pouteria sapota* fruits are ovoid to ellipsoid and are pointed at the apex. They are from 7.5 to 22.8 cm long and weigh from 0.227 to 2.3 kg. Fruits have a somewhat scurfy, dark brown, thick, woody skin. The flesh is soft and sweet with a smooth and creamy to somewhat finely granular texture with a salmon-pink, orange to deep red color. Fruits can have from one to four large, hard, oily, polished, spindle shaped, pointed kernels presenting a glossy brown appearance, a whitish hilum on the ventral side and a bitter-almond aroma (Standley and Williams, 1967; Pennington and Sarukhan, 1968; Pennington, 1990; Morton, 1987; Orwa *et al.*, 2009).

21.1.2 Worldwide importance

Areas of greatest production correspond to those where the largest number of trees are found and are those where the mamey sapote is native. In these areas, most trees are found in domestic gardens, as part of the natural flora, or in combination with other crops. Commercial fields of *Pouteria sapota* are not very common but some can be found in Mexico (Puebla, Veracruz, Oaxaca, Chiapas, Tabasco, Yucatan and Quintana Roo). In 1991, 2649 ha of commercial plantations of mamey sapote were reported in Mexico, mainly in Yucatan, Veracruz and Puebla. Guatemala is another important area of mamey sapote production, with levels reaching 50 000 tons in 1997 and exports to the US reaching 549 tons in 1999. The mamey sapote has been introduced to areas like Colombia, Venezuela, the Philippines, Cuba, Dominican Republic, Puerto Rico, Malaysia, Hawaii, Florida and Puerto Rico. Countries like Ecuador, Paraguay, Honduras and Costa Rica also produce mamey, although to a lesser extent (Azurdia, 2006).

21.1.3 Culinary uses, nutritional value and health benefits

Mamey sapote fruit are mainly used for their flesh whose nutrient content is shown in Table 21.1. Fruit can be eaten fresh by cutting them in half and removing the seed; the flesh can then be spooned from the half-shell. (See Plates XXXVI and XXXVII in the colour section between pages 274 and 275.) Ice cream, jam, conserves, milkshakes and pastes can be made with the mamey sapote flesh.

Mamey sapote trees are rarely used for their wood except when the fruit quality is poor. The wood is relatively durable, strong and easy to work with and can be used for cabinet work, furniture, carts, shelving and house frames (Orwa *et al.*, 2009).

The mamey seed contains 40–60% of an oil with vaseline consistency which is considered to have a great potential in the elaboration of soap, pharmaceutical and

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Table 21.1 Nutrient value of mamey sapote fruit (per 100 g of fruit)

Constituent	Approximate value
Water content	63.8%
Calories	126.0
Protein	3.1 g
Fat	0.1 g
Carbohydrates	31.8 g
Fibre	1.2 g
Ash	1.2 g
Calcium	121 mg
Phosphorus	30 mg
Iron	0.8 mg
Vitamin A	70 IU
Thiamin	0.01 mg
Riboflavin	0.05 mg
Niacin	1.9 mg
Ascorbic acid	40 mg

Source: Wu and Flores (1961)

cosmetic products. The oil is actually edible when freshly extracted (Aguilar, 1966). Among other medicinal properties attributed to the mamey sapote fruit are the oil contained in the kernel, which has been used as a skin ointment and as a remedy for hair loss. Some people use this oil as a palliative in eye and ear problems. In Mexico, the kernel coat is ground and taken to help with coronary, kidney and rheumatism problems (Azurdia, 2006; Orwa *et al.*, 2009). It can also be mixed with parched corn, or cornmeal, sugar and cinnamon to make a beverage called 'pozol' (Morton, 1987). The white latex has also been used as an antifungal for the skin or to remove warts.

Some toxic effects associated with the mamey sapote are related to the kernel which contains an elevated HCN content giving it stupefying properties. The leaves have also been reported to be poisonous; however, people in Costa Rica use them to make tea that is taken to treat arteriosclerosis and hypertension (Orwa *et al.*, 2009). The white latex that exudates from the mamey tree is irritant to the eyes and caustic to the skin, and care must be taken to avoid coming into contact with it (Morton, 1987).

21.2 Postharvest physiology

Mamey sapote is a climacteric fruit (Yahia, 2004). Mature fruit do not ripen on the tree; they only ripen when they have been detached. The fruit has high rates of respiration and degradation (Casas-Alancaster, 1977; Diaz-Perez *et al.*, 2000). It

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reaches a climacteric peak four days after harvest when it is kept at 25°C. Production of CO_2 ranges from 20–50 mg kg^{-1} h^{-1} before the climacteric peak and increases to about 110 mg kg^{-1} h^{-1} at the climacteric peak (Diaz-Perez *et al.*, 2000).

The flesh of mature mamey sapote fruit presents a yellow or pale colour that changes to orange or red in fully ripe fruits (Diaz-Perez *et al.*, 2000). The orange-red colour in ripe mamey sapote is due to the high concentration of carotenoids (130 mg kg^{-1}) (Casas-Alancaster, 1977), β-carotene being the most abundant (94% of the total carotenoids) (Morales-Vazquez, 1983). Browning of the flesh increases with ripeness and this is associated with the high concentration of phenolic compounds found in ripe fruit (0.3% of total phenolics). Soluble solids content (SSC) is increased during ripening. Mature fruit presented about 12% SSC while fully ripe fruit had 30–35%. SSC increases during ripening due, at least in part, to the degradation of starch into sugars. Starch content decreases from 14 to 5% with an associated increase in total sugars from 6 to 16%. Firmness of the mamey sapote fruit decreases with ripeness. Mature fruit presented a firmness value of 120 N (Newton) in mature fruit compared to 50 N in ripe fruit and almost 0 in overripe fruit (Casas-Alancaster, 1977). Acidity appears to be constant during ripening of mamey sapote fruit (Diaz-Perez *et al.*, 2000). Fruits of mamey sapote stored at 20°C and 50–60% relative humidity (RH) for 12 days showed a decrease in total phenolic content while the activity of polyphenol oxidase (PPO) increased. The decrease in phenolics was reflected in a reduction in the astringency. During ripening the activity of other enzymes such as peroxidase (POD), catalase (CAT), and superoxide dismutase (SOD) were increased. The content of soluble protein also increased during ripening (Alia-Tejacal *et al.*, 2005).

21.3 Maturity and quality components and indices

It is hard to say when the mamey sapote fruit are ready to be harvested. The fruit is usually harvested when the flesh begins to develop a red colour. The fruit matures when the newly exposed layer turns from green to pinkish-brown, orange, or red (Yahia, 2004). Fruit harvested when immature will fail to soften and their pulp will turn dark brown, and become inedible. According to Morton (1987), mamey sapote fruits that have ripened irregularly will develop a strong squash flavour.

21.4 Postharvest handling factors affecting quality

21.4.1 Temperature management

The number of days required for mature fruit to ripen depends on the storage temperature. Fruit harvested at the commercial stage and maintained at 27, 25, or 20°C reached ripeness after 4, 5, or 6 days, respectively. However, overripe fruit kept at more than 20°C developed off-odours and fungal growth (Diaz-Perez *et al.*, 2000).

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Fruit kept at 10 or 15°C ripened irregularly and did not soften evenly. In addition, the flesh in these fruits adhered to the kernel. Firmness in these fruits had a high level of variation, with values of 20–50 N in some areas of the fruit, but of more than 100 N in adjacent areas. The longer the fruit were held at this temperature, the more severe the damage, which was probably due to chilling injury (Diaz-Perez *et al.*, 2000).

Temperature also affects the SSC in mamey sapote fruit. Fruit kept at higher temperatures (27°C) had a higher SSC than those stored at 20°C (Diaz-Perez *et al.*, 2000). This increase is due in part to starch breakdown into sugars (Casas-Alancaster, 1977).

21.4.2 Water loss

Mamey sapote fruit stored for 6 days at 25°C lost 10.8% of their initial weight; however, their overall appearance was not affected, as few changes in the skin were detectable by eye (Diaz-Perez *et al.*, 2000).

21.5 Physiological disorders

21.5.1 Chilling injury

Mamey sapote fruit are chilling sensitive (Yahia, 2004) Typical symptoms of chilling injury include flesh browning, uneven ripening and softening, flesh adherence to the kernel, off-odours and flavours, and flesh lignification (Yahia, 2004). However, visual signs of chilling injury are hard to identify on the skin of mamey sapote fruits (Alia-Tejacal *et al.*, 2007). In mamey fruit stored at 2°C, the activity of the enzyme phenylalanine ammonia-lyase (PAL) was lower than that in fruit kept at 10°C. No significant changes were observed in the activity of POD but a constant reduction in PPO was observed in fruit stored at 2, 10 or 20°C (Perez-Tello *et al.*, 2009). Alia-Tejacal *et al*. (2005) also reported that antioxidant enzymes were negatively affected by storage temperatures lower than 10°C associated with chilling injury. Activities of PPO, CAT, and SOD decreased after storage at 5 and 10°C. In addition, the concentration of sugars is affected by exposure of mamey sapote fruit to low temperatures. Sucrose content decreased while fructose increased in fruit kept at 2°C as a result of chilling stress (Perez-Tello *et al.*, 2009). Storage at 5°C also delayed the decrease in total phenolic content (Alia-Tejacal *et al.*, 2005).

21.6 Pathological disorders

According to Morton (1987), anthracnose on the leaves and fruit stalks in rainy seasons is caused by the fungus *Colletotrichum gloeosporioides*. Infected fruit falls prematurely. Attack by the fungus *Phyllosticta sapotae* causing leafspot can occur in Cuba and the Bahamas but seldom in Puerto Rico. Black leaf spot *(Phyllachora sp.)* and root rot *(Pythium sp.)* may also occur in Florida. Other

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fungi including *Rhizoctonia* sp. and *Pythium splendens* may attack the root causing a detrimental effect on the tree vigour (Orwa *et al.*, 2009). After harvest, some fungi may attack the fruit, specifically *Pestalotia* and *Botryodiploidia*. However, the incidence of these fungi decreases as the fruit ripens. A reduction from 20% to 65% during ripening has been reported (Bautista *et al.*, 2002).

21.7 Insect pests and their control

Mamey sapote is very sensitive to infestation with fruit flies, especially with *Anastrepha serpentine* (Yahia, 2004; Yahia and Ariza, 2003; Ariza-Flores *et al.*, 2009). However, no quarantine treatment is used in Mexico for this fruit, and therefore the fruit's entry to many national and international markets is restricted. Yahia and Ariza (2003) and Ariza-Flores *et al.* (2009) exposed fruit of mamey sapote to different hot air treatments at 40, 43, 45, 46 or 50°C for 120, 150 or 180 minutes, and these were then stored at 10°C or 25°C for up to 15 days. Larvae and eggs mortality was achieved at 43°C for 120 minutes. This heat treatment did not cause fruit injury, while keeping at a minimum the loss of firmness, fruit mass, and colour. Other attempts have been made to establish a hot water treatment for mamey sapote (Granados and Utrera, 1996; Diaz-Perez *et al.*, 2001); however, more research is necessary to find the best conditions that not only eliminate fruit flies but also allow an acceptable shelf-life.

Other insects that occasionally attack the mamey sapote include the Cuban May beetle (*Phyllophaga bruneri*), the sugarcane rootstalk borer (*Diaprepes abbreviatus*), white peach scale (*Pseudaulacaspis pentagona*), Philephedra scale (*Philephedra sp.*) and green scale (*Coccus viridis*) (Orwa *et al.*, 2009).

21.8 Postharvest handling practices

21.8.1 Harvest operations

Harvest season depends on the climatic conditions and cultivar of mamey sapote. For instance, there are two harvest seasons in the Dominican Republic (summer and winter) while in Puerto Rico the harvest season starts in September and ends in early November (Azurdia, 2006).

Harvesting should be done carefully to avoid mechanical damage. The fruit is twisted until it breaks from its stem. Poles with knives at the end are also used to collect the fruit. The fruit should not be left to fall on the ground.

21.8.2 Packinghouse practices

Some growers clean the skin of the fruits with a brush to remove possible dirt. The peduncle is also cut to improve appearance. The fruit is packed in 3 kg capacity fibreboard flat boxes, using sleeves or excelsior to prevent physical damage (McGregor, 1987).

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21.8.3 Control of ripening and senescence

Storage of mamey sapote in perforated polyethylene at 25°C and external 40–45% RH reduced weight loss by 50% while slowing down changes in SSC and colour development as compared to control fruit (Villanueva-Arce *et al.*, 1999). Use of Peakfresh and Kleen Pack films and storage at 20.5°C ± 2.0°C and 29.4% RH was reported to reduce weight loss by about 8% and delayed ripening for 3 days, keeping fruit quality (Ramos *et al.*, 2005). Good fruit quality and no incidence of physiological disorders was achieved after storing mamey sapote for 3 weeks at 15°C and a continuous flow of 5.1 kPa CO_2 and 5.6 kPa O_2 and balance N_2 (Manzano, 2001). Storage atmosphere containing 10 kPa CO_2 and 5 kPa O_2 in a static system caused a reduction in ethylene production, thus delaying ripening, even after transferring the fruit to room temperature (Martinez-Morales *et al.*, 2004, 2005). Treatment with carnauba wax and 1-methyl cyclo propane (1-MCP) was evaluated in mamey sapote fruit, and was reported to maintain good quality. Furthermore, 1-MCP had a stronger effect on extending fruit shelf-life than waxing (Ergun *et al.*, 2005).

Ethylene applications (176 ppm) for 24 h to mamey sapote fruit at 20°C and 25°C accelerated ripening by 1.4 days (Table 21.2). The respiration peak occurred one day earlier at 25°C than at 20°C. The quality of the fruit was improved regarding total sugars content. Other parameters such as firmness, colour, phenolics and weight loss were not affected by ethylene treatment (Martínez Morales *et al.*, 2003).

Table 21.2 Ripening rates in fruits of mamey sapote after ethylene treatments

Treatment	Ethylene (ppm)	Temperature (°C)	Days until ripeness
1	0	20	5.2
2	50	20	4.0
3	176	20	3.8
4	0	25	4.2
5	50	25	4.2
6	176	25	3.8

Source: Martínez Morales *et al.* (2003)

21.8.4 Recommended storage and shipping conditions

Transit and storage life is extended for up to 2 to 6 weeks when fruit are kept at 13–18°C and 85–90% RH (Yahia, 2004; Azurdia, 2006).

21.9 Processing

Freezing of the flesh is probably one of the processing techniques with good potential for mamey sapote (Azurdia, 2006). Fruit are stored in the processing plant until ripe. Ripe fruits are washed manually using either chlorinated water or detergent followed by a second wash with chlorinated water. Then, fruit are cut on

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stainless steel tables and flesh is extracted manually, discarding the kernel and skin. Total yield ranges from 25 to 50% of the total fruit weight. Flesh is then ground and packed in plastic bags containing 392 g that are sterilized by heating at 85°C for 15 min, followed by another 15 min at 5°C and finally 2 hours at −15°C. Bags are placed in carton containers of 5–10 kg and stored in cold rooms at −15°C for 2–3 weeks before being marketed. Frozen fruit are also prepared by first washing the fruits using chlorinated water (200 ppm) for 30 min. Packing of the fruits is done on stainless steel tables, placing fruits in plastic bags that are stored in carton boxes. Each box contains approximately 40–45 fruits and is stored in a cold room.

Flour of mamey sapote is prepared by washing and extracting the fruit using the same procedure as for frozen flesh production. However, in this case, the pulp is cut in 5 × 5 mm and placed on drying sheets. Dehydration is obtained with temperatures of 70°C for 12–40 hours until a relative humidity of 7–10% is reached. The dried pulp is then ground and packed in 45 kg bags. The yield for this process is 1 kg of flour for every 13.3 kg of pulp. The flour is mainly used for baking.

Dehydrated flesh is processed in the same way as the one outlined for flour production, except that the quality requirement of the fruit used is not as high as in the flour process. Final humidity content of the dehydrated flesh is about 16%.

Mamey sapote candy can be made by grinding the flesh and then mixing it with sugar and heating until a paste is formed. After cooling, blocks are formed, cut and wrapped for selling. Shelf-life of these products is short (15 days) and therefore their potential for exportation is limited. Frozen lollipops are made by mixing the mamey sapote flesh with sugar and water in a 3:2:2 ratio and then blending and freezing. Mamey yogurt is made with the frozen flesh by adding it to a yogurt base (Azurdia, 2006).

21.10 Conclusions

Mamey sapote is a highly perishable climacteric fruit with postharvest losses reaching up to 25% in some areas like Guatemala. Although mamey sapote fruit are mainly consumed for their flesh, different products can be elaborated from the oil contained in the seed. Storage temperature is an important factor in mamey handling since this fruit is sensitive to chilling injury. Processing of mamey sapote pulp into different products has great potential, especially considering that these products would be easier to transport to different markets. Frozen whole fruit or mamey flesh are some of the best options for exporting mamey sapote without worrying about postharvest deterioration and quarantine restrictions. Controlled/modified atmospheres constitute a possible option for extending mamey shelf-life.

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(a)

(b)

(c)

(d)

Plate XXXV (Chapter 20) (a) Mamey apple tree; (b)–(c) mamey apple fruit; (d) exterior and interior of mamey apple fruit.

(a)

(b)

(c)

Plate XXXVI (Chapter 21) (a)–(c) Mamey sapote fruit.

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(a)

(b)

Plate XXXVII (Chapter 21) Mamey sapote fruit sold in the street in Mexico.

Plate XXXVIII (Chapter 22) External and internal colour changes during ripening of 'Tommy Atkins' mango fruit.

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22

Mango (*Mangifera indica* L.)

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Abstract: Mango is a very important fruit, cultivated in several tropical and subtropical regions, and its distribution in world trade is expanding. Strategies to extend mango postharvest life are based on control of ripening, ethylene production and action, decay and pests. The fruit is sensitive to chilling injury and the subsequent need to use relatively high temperature for storage and transport limits the postharvest life of the fruit. Successful handling of mangoes in which ripening has commenced is problematic due to the fruit's short shelf life. There is a need for the development of improved storage and ripening techniques. In addition, genetic transformation to manipulate the progression and uniformity of ripening and softening has the potential to greatly improve postharvest shelf life.

Key words: *Mangifera indica*, postharvest, physiology, technology, handling, processing.

22.1 Introduction

Mangoes (Fig. 22.1) are among the most widely cultivated and consumed fruits in tropical and subtropical regions. Mango consumption in temperate-zone countries in particular has been increasing dramatically in recent years. Successful postharvest handling of mangoes requires knowledge of the postharvest physiology of the fruit and understanding of how this determines handling practices to maintain and develop high quality fruit (Yahia, 2005; Brecht and Yahia, 2009; Yahia *et al.*, 2006a). The postharvest handling system used for mangoes also depends on the marketing system in which the fruit will be sold. This includes factors such as distance to the market, the desires and expectations of the consumers in that market, and the availability of labour, technology and infrastructure required for various handling options (Yahia *et al.*, 2006a).

For mangoes in particular, successful postharvest handling involves managing the ripening process and avoiding quality loss due to physical damage and decay

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Fig. 22.1 Mango tree and fruit.

(Yahia, 2005; Yahia *et al.*, 2006a). As mango fruit mature on the tree and begin to ripen, eating quality improves but potential marketable life decreases due to the difficulty of controlling the ripening changes once they have been initiated, and increased bruising susceptibility and decay. Also, susceptible mango varieties tend to break down further internally the longer they are left on the tree (Yahia, 2005; Yahia *et al.*, 2006a) (see Plate XXXVIII in the colour section between pages 274 and 275). However, being climacteric, mangoes can be harvested at a mature but unripe stage of development (termed the mature-green stage) and stored for some time in the unripe state as long as the initiation of ethylene production, and hence ripening, is avoided (Yahia, 2005; Yahia *et al.*, 2006a; Brecht and Yahia, 2009) (Plate XXXIX). The initiation of ripening can be delayed by prompt cooling and storage at a low temperature and/or by changing the composition of the storage atmosphere so that the oxygen (O_2) level is reduced and the carbon dioxide (CO_2) level is raised by using modified atmosphere (MA) or controlled atmosphere (CA) (Yahia, 1997; 1998a; 1998b; 2009; Yahia and Singh, 2009). However, there are limits to the levels of temperature, O_2 and CO_2 that can be tolerated by mangoes, and these limits are affected by a number of factors, primarily the cultivar, maturity stage, storage temperature and storage time (Yahia *et al.*, 2006a).

The increasing volumes of mangoes in international trade have shifted the mode of transport from primarily air freight to marine containers on board ocean-going vessels (Yahia, 2005; Yahia *et al.*, 2006a). This shift from rapid air freight transportation to slower marine shipping has been possible only because of strict attention to fruit maturity and temperature control. MA/CA in marine

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shipping is also becoming more commonly used as a method to control ripening and deterioration (Yahia, 1997; 1998a;b; 2009; Yahia and Singh, 2009), thus allowing fruit of more advanced maturity (and hence better quality) to be shipped.

22.1.1 Botany, morphology and structure

The mango fruit is a fleshy drupe, consisting of skin (epicarp) and edible flesh (mesocarp) surrounding a fibrous, hard stone (endocarp) containing a single seed. The seed may be either monoembryonic or polyembryonic, with fruit of the former classified as Indian and the latter as Indo-Chinese (Yahia *et al.*, 2006a). Indian mango types tend to have roundish fruit with varying amounts of red anthocyanin pigment in the skin that develops in response to light ('blush') while Indo-Chinese types are usually elongated and solid green or yellow when ripe. Because hybridization occurs easily between the two types, mango cultivars exist with wide ranges of genotypic and phenotypic variation.

There are large differences in size, shape, appearance and physiological characteristics between different cultivars. For example, the average weight of different mango fruit cultivars ranges from less than 80 to more than 800 g (Fig. 22.2).

22.1.2 Worldwide importance and economic value

Mango is one of the oldest and most important fruits. Global production of mangoes was about 30 million tons (MT) in 2010 (FAO, 2010) and it is the second largest tropical fruit crop in the word, after banana. Mango has been cultivated in India for more than 4000 years, and today grows in more than 80 countries in tropical and sub-tropical regions. More than 70% (about 23 MT) of the crop is produced in Asia and the Pacific, about 13% (about 4 MT) in Latin America and the Caribbean, and less than 10% (almost 3 MT) in Africa. India remains the world's largest mango producing country with 40% of total global production (over 12 MT) (Yahia *et al.*, 2006a). In recent years, the most significant increase in mango production in Asia and the Pacific region has been in China. Production in Mexico, the largest mango producing country in Latin America and the Caribbean and the largest mango exporting country in the world, is close to 2 MT (Yahia *et al.*, 2006a).

Although the total amount of mango trade in the world is insignificant compared to other fruit crops, as less than 10% of the crop produced is exported, it has become increasingly important in the international trade in recent years. About 20 or 30 years ago, mango was considered an exotic, rare fruit in many countries, especially in Europe and in North America, but nowadays, mango is commonly marketed in most countries. For example, mango was until recently the fastest growing fruit in terms of consumption in the US market. There has been a yearly increase of about 10% in mango import volumes in the US market in the last two decades, and it has became a popular speciality fruit in that country (Yahia *et al.*,

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Fig. 22.2 'Manila' fruit.

2006a). Mango consumption in the US increased from 0.25 pounds per person in 1980 to 0.54 pounds per person in 1990, and 1.84 pounds per person in 2000 (Yahia *et al.*, 2006a). Mango consumption is also increasing in the rest of the world, as the fruit is becoming more available in the world market. This is due to improved preharvest and postharvest handling techniques, including available quarantine treatments, an increase in sea transport and in the use of MA and CA (Yahia, 2005; Yahia *et al.*, 2006a).

Mango imports/exports were about 1.5 MT in 2010, and are expected to grow, with Mexico being the biggest exporter (41% of the world market) (Sauco, 2004)

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and the US (about 450 000 T) and the Eu (about 500 000 T) being the top importing areas (FAO, 2010; Yahia *et al.*, 2006a). Other important exporting countries are the Philippines (7.6%) and Pakistan (7.8%) (Sauco, 2004). Mango production and export are expected to grow further especially in Asia and the Pacific, supported by reasonably strong demand and strong forecast growth in China, Thailand, the Philippines and India. Import to the US takes place throughout the year, but there is a pronounced seasonality in the European market, with large quantities imported during the second (April–June) and fourth (October–December) quarters (Yahia *et al.*, 2006a). France, the Netherlands and the United Kingdom are the primary import markets in the EU, and imports to Spain are increasing slightly.

A variety of mango types are available in the market including different colours (green, yellow, coloured), shapes, appearances and flavours. Mango cultivars are many and are commonly classified into two groups depending on their ability to reproduce from seeds: monoembryonic and polyembryonic. Monoembryonic cultivars are hybrid in origin and must be reproduced by asexual propagation. Polyembryonic cultivars are those where many embryos may develop from diploid parent nucellar tissue after fertilization of the egg cell. Since only one embryo is of hybrid origin in these polyembryonic types, seedlings are usually identical to the tree from which the fruit is harvested. Polyembryonic cultivars are mostly of Philippine or Indo-Chinese origin. Pandey (1985) listed 793 mango cultivars from all over the world. In India, the biggest producer of mango in the world, there are more than a thousand cultivars, but only about 25 to 40 cultivars are grown commercially. Almost all of the cultivars growing in India are monoembryonic types, and over a dozen cultivars are polyembryonic types. Polyembryonic cultivars reported from India include 'Bappakai', 'Chandrakaran', 'Goa', 'Kurukkan', 'Olour', 'Bellary', 'Kasargod', 'Mazagaon', 'Nileswar Dwarf' and 'Salem' (Kalra *et al.*, 1994). Polyembryonic cultivars reported from other parts of the world include 'Cambiodiana', 'Carabao', 'Cecil', 'Higgins', 'Paho', 'Peach/Apricot', 'Pico', 'Sabre', 'Saigon', 'Simmonds', 'Sammini' and 'Strawberry' (Yahia *et al.*, 2006a). In the ASEAN region (the Philippines, Malaysia, Indonesia, Singapore, Thailand) there are over 500 cultivars, but only a few are cultivated commercially. Of 53 cultivars in the Philippines only 2 ('Carabao' and 'Pico') are cultivated commercially (Yahia *et al.*, 2006a). In Hawaii, 'Pierie' and 'Haden' are the most important commercial cultivars. In Florida, an important collection of mango germplasm exists, but 'Tommy Atkins' is the most important commercial cultivar (Malo, 1977). In Mexico, 'Manila' (Figure 22.2), 'Ataulfo', 'Keitt', 'Kent', 'Haden' and 'Tommy Atkins' are the most important commercial cultivars (Yahia, 1997; Yahia *et al.*, 2006a). In South Africa, 'Zill', 'Kent' and 'Haden' are the most important cultivars grown (Hobson, 1969). 'Common' and 'Kensington Pride' are produced in Australia (Queensland Department of Agriculture, 1977), and 'Fiji', 'Peach', 'Jarra', 'Parrot' and 'Kerosene' are produced in Fiji (Iqbal, 1982). The most important Egyptian commercial cultivars include 'Alphonso', 'Ewais', 'Hindy

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Sinnara', 'Mabrouka', 'Misk', 'Pairi', 'Sukkary', 'Taimour' and 'Zebda' (Yahia, 1997; 2005; Yahia *et al.*, 2006a).

22.1.3 Nutritional value and health benefits

Mango fruit are a rich source of vitamin C (Table 22.1), and the content decreases during ripening (Thomas, 1975; Vinci *et al.*, 1995). 'Raspuri' mango contains 300 mg 100 g^{-1} fresh fruit of vitamin C during the early stages of development, but decreases to about 39.1–69.5 mg 100 g^{-1} at maturity (Siddappa and Bhatia, 1954). The vitamin C content ranged between 13 and 178 mg 100 g^{-1} in the ripe fruit of 50 cultivars surveyed by Singh (1960). In fully grown mango fruit of cultivars grown in Puerto Rico vitamin C ranged between 6 and 63 mg 100 g^{-1} (Iguina de George *et al.*, 1969). Vitamin C content was 105.2, 65.7 and 17.3 mg 100 g^{-1} in 'Langra', 'Ashwini', and 'Fazli' mangoes, respectively (Gofur *et al.*, 1994), and decreased rapidly 5 to 7 weeks after fruit set, and when ripe fruit were stored at room temperature.

Vitamin B1 (thiamine) in two mango cultivars was reported to be 35–60 μg 100 g^{-1}, and vitamin B2 (riboflavin) in three cultivars was 45–55 μg 100 g^{-1} (Stahl, 1935). Thiamine content of four Philippine cultivars was 57–600 μg 100 g^{-1}, and riboflavin content of three cultivars was 37–730 μg 100 g^{-1} (Quinones *et al.*, 1944). Folic acid in green mangoes was 36 mg 100 g^{-1} (Gosh, 1960) (Table 22.1).

Mango fruit is also a rich source of carotenoids (Table 22.1), some of which, such as β-carotene, β-cryptoxanthin, zeaxanthin, luteoxanthin isomers, violaxanthin and neoxanthin (all-trans and cis), are pro-vitamin A (Mercadante *et al.*, 1997; Yahia *et al.*, 2006b; Ornelas-Paz *et al.*, 2007; 2008; 2010; Yahia and Ornelas-Paz, 2010). Carotenoids are the pigments responsible for the yellow-orange colour of mango exocarp and mesocarp (Vázquez-Caicedo *et al.*, 2004). Total carotenoid content rose from 12.3 to 38.0 μg g^{-1} in 'Keitt' and from 17.0 to 51.2 μg g^{-1} in 'Tommy Atkins' from the mature-green to the ripe stage (Mercadante and Rodriguez-Amaya, 1998), and ripening alterations occurred principally in violaxanthin and β-carotene. *Trans*-β-carotene, *trans*-violaxanthin, and 9-*cis*-violaxanthin in 'Keitt' mangoes increased from 1.7, 5.4, and 1.7 μg g^{-1}, respectively, in the mature-green fruit to 6.7, 18.0, and 7.2 μg g^{-1} in the ripe fruit (Mercadante and Rodriguez-Amaya, 1998). In 'Tommy Atkins' these carotenoids increased from 2.0, 6.9, and 3.3 μg g^{-1} to 5.8, 22.4, and 14.5 μg g^{-1}, respectively, during ripening. Geographic effects were reported to be substantial (Mercadante and Rodriguez-Amaya, 1998). Some of the *cis* and *trans* isomers of pro-vitamin A reported in 'Haden' and 'Tommy Atkins' mangoes include 13-cis-β-carotene (trace amounts), trans-β-carotene (12.5–15.5 μg g^{-1}) and trans-α-cryptoxanthin (0.3–0.4 μg g^{-1}) (Godoy and Rodriguez-Amaya, 1994). In processed mango juice, violaxanthin was not detected, auroxanthin appeared at an appreciable level, and β-carotene was the principal carotenoid (Mercadante and Rodriguez-Amaya, 1998). The major carotenoid in 'Bourbon', 'Haden', 'Extreme', 'Golden' and 'Tommy Atkins' mangoes was β-carotene (48–84% of the total), while

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Table 22.1 Composition of the edible portion of mango fruit

Nutrient	Value per 100 g edible portion
Water g	81.71
Energy k cal	65
Energy kj	272
Protein g	0.51
Total lipid (fat) g	0.27
Ash g	0.50
Carbohydrate, by difference g	17.00
Fibre, total dietary g	1.8
Sugars, total g	14.80
Minerals	
Calcium mg	10
Iron mg	0.13
Magnesium mg	9
Phosphorus mg	11
Potassium mg	156
Sodium mg	2
Zinc mg	0.04
Copper mg	0.110
Manganese mg	0.027
Selenium μg	0.6
Vitamins	
Vitamin C (total ascorbic acid) mg	27.7
Thiamin mg	0.058
Riboflavin mg	0.057
Niacin mg	0.584
Pantothenic acid mg	0.160
Vitamin B-6 mg	0.134
Folate, total μg	14
Folic acid μg	0
Folate, food μg	14
Vitamin B-12 μg	0.00
Vitamin A IU	765
Retinol μg	0
Vitamin E (α-tocopherol) mg	1.12
Vitamin K (phylloquinone) μg	4.2
Lipids	
Fatty acids, total saturated g	0.066
4:0 g	0.000
6:0 g	0.000
8:0 g	0.000
10:0 g	0.000
12:0 g	0.001
14:0 g	0.009
16:0 g	0.052
18:0 g	0.003
Fatty acids, total monounsaturated, g	0.101
16:1 undifferentiated g	0.048
18:1 undifferentiated g	0.054

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Table 22.1 continued

Nutrient	Value per 100 g edible portion
20:1 g	0.000
22:1 undifferentiated g	0.000
Fatty acids, total polyunsaturated g	0.051
18:2 undifferentiated g	0.014
18:3 undifferentiated g	0.037
18:4 g	0.000
20:4 undifferentiated g	0.000
20:5 n-3 g	0.000
22:5 n-3 g	0.000
22:6 n-3 g	0.000
Cholesterol g	0
Amino acids	
Tryptophan g	0.008
Threonine g	0.019
Isoleucine g	0.018
Leucine g	0.031
Lysine g	0.041
Methionine g	0.005
Phenylalanine g	0.017
Tyrosine g	0.010
Valine g	0.026
Arginine g	0.019
Histidine g	0.012
Alanine g	0.051
Aspartic acid g	0.042
Glutamic acid g	0.060
Glycine g	0.021
Proline g	0.018
Serine g	0.022
Other	
Ethanol g	0.0
Caffeine mg	0
Theobromine mg	0
β-Carotene μg	445
α-Carotene μg	17
β-Cryptoxanthin, μg	11
Lycopene μg	0
Lutein + zeaxanthin μg	0

Source: USDA National Nutrient Database for Standard Reference, Release 20 (2007)

epoxycarotenoids (violaxanthin, luteoxanthin and mutatoxanthin) constituted 13–49% of the total (Godoy and Rodriguez-Amaya, 1989). Mean vitamin A in these mangoes (retinol equivalents $100\,g^{-1}$) ranged from 115.3 ('Haden') to 430.5 ('Extreme'). Children in Senegal with normal cytology had higher serum retinol

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and β-carotene levels than those with abnormal cytology after massive oral doses of vitamin A and consumption of mangoes (Carlier *et al.*, 1992). Mango retinol has been shown to be highly bioavailable (82% efficiency) by estimating vitamin A and carotene reserves in the liver and plasma of rats (Yuyama *et al.*, 1991; Ornelas-Paz *et al.*, 2010). During mango fruit ripening, vitamin A increases; ripe mangoes are ten times richer in carotene than partially ripe fruit, while unripe green mangoes contain only trace amounts (Modi and Reddy, 1967). Mevalonic acid, a precursor of carotenoids, increased progressively during mango ripening (Modi and Reddy, 1967). Vitamin A equivalents in 100 g of mango fruit are 1000 to 6000 IU (Singh, 1960). The β-carotene content of the fruit of 30 mango cultivars in Puerto Rico ranged from 400 to 800 IU 100 g^{-1} fresh fruit (Iguina de George *et al.*, 1969). The development of β-carotene in mangoes held at 16–21°C was lower than that at 20–28°C (Vazquez-Salinas and Lakshminarayana, 1985). Jungalwala and Cama (1963) identified 16 different carotenoids in 'Alphonso' mangoes, and β-carotene accounted for 60% of the total. Of the oxycarotenoids, luteoxanthin, violaxanthin, and cis-violaxanthin were present in significant amounts. All the oxycarotenoids were present as β-carotene derivatives, mostly as epoxides of zeaxanthin. Variation in carotenoid content, as in many other constituents, is due to several factors, i.e., cultivar, geography, climate, storage/processing conditions and analytical procedures employed. All-*trans*-β-carotene and the dibutyrates of all-*trans*-violaxanthin and 9-*cis*-violaxanthin are the main carotenoids in 'Ataulfo' and 'Manila' mangoes (Yahia *et al.*, 2006b; Yahia and Ornelas-Paz, 2010; Ornelas-Paz *et al.*, 2008). The content of these carotenoids during fruit ripening increased exponentially in 'Ataulfo' and exponentially or in a second-order polynomial manner in 'Manila'. Equations to predict the content of the most important carotenoids in 'Manila' and 'Ataulfo' mangoes on the basis of their internal and external colour values were obtained by Ornelas-Paz *et al.* (2008).

The content of α-tocopherol is approximately 0.5 mg 100 g^{-1} in an unidentified mango cultivar from Costa Rica (Burns *et al.*, 2003), while the USDA Nutrient Database (2007) indicates an α-tocopherol content of 1.12 mg 100 g^{-1} (Table 22.1). Ornelas-Paz *et al.* (2007) found that α-tocopherol is the only detectable tocopherol in seven mango cultivars; 'Haden' and 'Tommy Atkins' mangoes had the highest amounts (380 and 470 μg 100 g^{-1}), with 200 to 250 μg 100 g^{-1} in the other cultivars.

Mango fruit are rich in several other types of antioxidant phytochemicals such as phenolics (Ornelas-Paz *et al.*, 2007; Rocha-Ribeiro *et al.*, 2007; Yahia, 2010). The loss of astringency during mango fruit ripening is associated with the decrease in phenolic content (Selvaraj and Kumar, 1989). The phenolic content of mango fruit is high at the early stage of development, decreases during ripening and remains fairly steady (Lakshminarayana *et al.*, 1970). The peel of mango fruit had a higher phenolic content than the pulp at all stages of fruit development (Jain, 1961; Lakshminarayana *et al.*, 1970). Polyphenoloxidase (PPO) activity increased slightly from harvest maturity to half-ripe stage and then declined in 'Banganapalli', 'Dasheri', 'Fazli' and 'Langra', and decreased in 'Alphonso',

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'Suvarnarekha' and 'Totapuri' mangoes (Selvaraj and Kumar, 1989). PPO isolated from 'Haden' mango was found to be active towards the o-diphenolic compounds, showing higher activity in the presence of catechol, followed by chlorogenic acid, but not with monophenols (Park *et al.*, 1980).

Mango consumption has been shown to exert important health benefits (Yahia, 2010). Botting *et al.* (1999) showed that mango fruit have antimutagens and the heterocyclic amine 2-amino-3-methylimidazo[4,5-*f*]quinoline. The glucose area in type 2 (non-insulin-dependent) diabetes mellitus was lower after mango ingestion than after the ingestion of durian, rambutan and pineapple, and the insulin area was lower than after durian ingestion of the equivalent carbohydrate content. Percival *et al.* (2006) observed that whole mango juice inhibited cell proliferation in the leukemic cell line HL-60 and also inhibited the neoplastic transformation of BALB/3T3 cells. Garcia-Solis *et al.* (2008) studied the effect of 'Ataulfo' mango consumption on chemically induced mammary carcinogenesis and plasma antioxidant capacity in rats treated with *N*-methyl-*N*-nitrosourea (MNU). Rats treated with MNU had no differences in mammary carcinogenesis (incidence, latency and number of tumours), and none in plasma antioxidant capacity.

22.2 Fruit development and postharvest physiology

22.2.1 Fruit growth, development and maturation

Fruit set in mango occurs when the conditions for cross pollination are favourable. In contrast to other drupes, the fruit of which follow a double sigmoidal growth pattern, mango fruit growth follows a simple sigmoidal pattern (Lizada, 1993) There is rapid cellular growth for about 3 weeks, followed by cell enlargement for the subsequent 4 weeks (Singh *et al.*, 1937). The highest rates of fruit growth precede the hardening of the stone and are correlated with peak levels of auxins and gibberellins (Ito *et al.*, 1997). Early growth, preceding stone hardening, is due to a combination of cell division and enlargement and can account for 70 to 80% of the total fruit growth (Singh, 1954). Growth slows during stone hardening and is associated only with cell enlargement (Chattopadhyaya *et al.*, 1978). Attainment of maximum fruit size can take from 10 to 28 weeks after fruit set and is coincident with physiological maturity. Starch content in the flesh reaches a maximum at this point and ripening follows (Tandon and Kalra, 1983).

22.2.2 Respiration, ethylene production and ripening

Mango is a climacteric fruit, exhibiting a climacteric pattern of respiration and an increase in ethylene production during ripening (Cua and Lizada, 1990; Reddy and Srivastava, 1999; Lalel *et al.*, 2003; Brecht and Yahia, 2009). Respiration is very high after fruit set and then declines and is maintained at a low rate until fruit ripening begins (Brecht and Yahia, 2009; Yahia *et al.*, 2006a). The initiation of

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ethylene production within the fruit triggers and coordinates the changes that occur during ripening. These include: (1) flesh colour from greenish yellow to yellow to orange in all cultivars (Plates XXXVIII and XXXIX); (2) skin colour from green to yellow in some cultivars (Plate XXXIX); (3) chlorophyll decreases and carotenoid content increases; (4) flesh firmness decreases and juiciness increases; (5) conversion of starch into sugars; (6) total soluble solids (TSS) content increases; (7) titratable acidity decreases; (8) characteristic aroma volatiles increase; (9) CO_2 production rate increases from about 40–50 to 160–200 mg $kg^{-1}h^{-1}$ at 20°C; and (10) ethylene production rate increases from about 0.1–0.2 to 1–3 μL $kg^{-1}h^{-1}$ at 20°C. Gowda and Huddar (2000) found the changes in eight mango selections during ripening included reductions in fruit weight, volume, length, thickness, firmness, pulp content, pulp to peel ratio, starch and vitamin C, and increases in TSS, pH, total sugars, sugar:acid ratio, pulp carotenoid content and peel colour. Ripening of mango is inhibited while fruit are attached to the tree, and respiration and ripening are stimulated upon detachment (Lakshminarayana, 1973). Burg and Burg (1962) reported that ethylene levels in the tissues of mature-green, attached mango fruit were relatively high (1.87 μl L^{-1}) and suggested that this ethylene was ineffective for promoting ripening on the tree due to a ripening inhibitor supplied by the tree. Mangoes can be ripened after harvest when picked at physiological maturity (mature-green, shown in first 2–3 stages of Plates XXXVIII and XXXIX). Ripening and natural senescence of mango fruit is aggravated and promoted by ethylene, mechanical injury and high temperature, and can be delayed by lower temperature, elimination of mechanical damage and reducing ethylene production and/or action (Yahia *et al.*, 2006a).

Respiration patterns and ripening behaviour vary among cultivars, with different climatic conditions and growing locations (Krishnamurthy and Subramanyam, 1970). The respiratory peak in 'Alphonso' mangoes harvested mature-green occurred 5 days after harvest, and the fruit ripens within 7 or 8 days (Karmarkar and Joshi, 1941), while in 'Kent' and 'Haden' mangoes the peak occurred on days 9 and 11, respectively (Burg and Burg, 1962), and in 'Pairi' mangoes on day 9 (Krishnamurthy and Subramanyam, 1970). These differences are normal due to differences in location, climatic conditions, orchard and tree conditions, and especially postharvest conditions used in the different studies. The rise in the climacteric respiration in 'Dashehari', 'Amrapali' and 'Rataul' mangoes coincides with the highest level of sucrose and polygalacturonase (PG) activity in ripening fruit (Kalra and Tandon, 1983).

Fruit slicing affects respiration rate (Allong *et al.*, 2001). Slicing of mature-green 'Julia' and 'Graham' mangoes increases respiration rate immediately after cutting, but it decreases significantly within the first 12 h of storage at 5 or 10 °C, yet still remains at levels above that of the intact fruit throughout the storage period. The effects of slicing on half-ripe and firm-ripe fruit include an initial increase in respiration followed by a decline to levels equal to that of the intact fruit.

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Mangoes have a moderate ethylene production peak of 1 to 3 μl $kg^{-1}h^{-1}$ during ripening at 20 °C (Yahia, 2005; Brecht and Yahia, 2009; Yahia *et al.*, 2006a). Ethylene, applied directly or as ethrel, induces faster and more uniform fruit softening (Lakshminarayana, 1973; Barmore, 1974; Lakshminarayana *et al.*, 1974; Sornsrivichai and Waru-Aswapti, 1989). Ethylene treatment can be prior to shipping (Barmore and Mitchell, 1975). There is disagreement regarding the effect of ethylene treatment on quality (Chaplin, 1988), and this may be related to maturity when treated; treatment of immature fruit may lead to softening and poor flavour. Only a small concentration of exogenous ethylene (≥0.005 μl L^{-1}) is needed to initiate mango ripening (Wills *et al.*, 2001), and the small amount of ethylene present in the fruit at harvest is sufficient to initiate this process (Burg and Burg, 1962). In 'Carabao' mangoes, the peak of ethylene production occurs 110 days after flower initiation, and declines as fruit approaches full maturity (Cua and Lizada, 1990). The content of 1-aminocyclopropane-1-carboxylic acid (ACC), the immediate precursor of ethylene, increases in different tissues (peel, outer and inner mesocarp) during ripening, while ACC oxidase (ACO), which catalyses the conversion of ACC to ethylene, and ethylene production decline (Reddy and Srivastava, 1999). Fruit peel has the highest levels of ethylene and ACO and less ACC accumulation than the outer and inner mesocarp at the mature-green stage. The inner mesocarp has less ACO activity and high ACC accumulation during the ripening process compared to peel; levels in the outer mesocarp are intermediate between those in the peel and inner mesocarp. Changes in the ability to convert ACC to ethylene in the peel are not related to changes in ripening parameters in the fruit pulp (Lederman *et al.*, 1997). Fruit slicing had no measurable effect on ethylene production in 'Julia' and Graham' mangoes (Allong *et al.*, 2001). Treatment of mango fruit with acetaldehyde or ethanol vapour (0.1, 0.5 or 1%) has concentration-dependent inhibitory effects on ethylene production (Burdon *et al.*, 1996). Application of ACC to acetaldehyde- or ethanol-treated fruit discs indicates that acetaldehyde can completely eliminate increased ACO activity, whereas ethanol cannot (Burdon *et al.*, 1996). Accordingly, Burdon *et al.* (1996) suggested that acetaldehyde can either inhibit ACO activity directly or prevent the increase in the enzyme, thereby providing a possible mechanism for retarding fruit ripening.

22.2.3 Compositional changes during fruit maturation and ripening

Several important metabolic changes occur during the maturation and ripening of mangoes, and some of those are useful as maturity and quality indices (Yahia, 2005; Yahia *et al.*, 2006a; Ketsa *et al.*, 1991).

Sugar changes are very important for organoleptic attributes in mango fruit. Fruit flavour is mostly a balance between the content of sugars and organic acids (Medlicott and Thompson, 1985) as well as aromatic volatiles. Quality enhancement has been used to determine properties critical to flavour acceptability of mangoes, and focus group interviews have been conducted to determine

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sensory attributes important to mango purchase and consumption (Malundo, 1996). Kapse *et al.* (1989) determined that increasing TSS and decreasing acidity increases flavour ratings of mango fruit. Sugars and acids also enhance perception of specific flavour notes in mango, including aroma (Malundo *et al.*, 2001). Sucrose is the predominant sugar in ripe mango fruit (Medlicott and Thompson, 1985), while the predominant acid is citric (Lizada, 1993). Several factors affect sugar and acid contents in mango, including cultivar (Gowda *et al.*, 1994), stage of maturity at harvest (Tandon and Kalra, 1983), postharvest treatments (Kumar *et al.*, 1993) and storage conditions (Vazquez-Salinas and Lakshminarayana, 1985).

The increase in soluble sugars is a major change during mango fruit ripening, and is the most important compositional change related to mango flavour, i.e., sweetness. Starch content increases during mango fruit development and it is almost completely hydrolysed to simple sugars during ripening (Medlicott *et al.*, 1986; Selvaraj *et al.*, 1989; Kumar *et al.*, 1994; Ito *et al.*, 1997). In 'Alphonso' mangoes, starch content is about 14% at the immature stage and decreases to about 0.3% at the ripe stage. It is almost undetectable in 'Irwin' mangoes after ripening, whereas sucrose increases significantly and fructose increases slightly (Ito *et al.*, 1997). Starch content decreases slightly during ripening of 'Haden', but is insufficient to account for the observed increase in sucrose (Castrillo *et al.*, 1996). Ripe mango contains up to 10–20% total sugars, depending on the cultivar and the stage of ripeness. At the beginning of ripening, reducing sugars make up most of the sugar content, while there are more non-reducing (about 17%) than reducing (3%) sugars in ripe fruit. In a study by Medlicott and Thompson (1985), sucrose contributed 57% of the total sugar in ripe 'Keitt' mangoes, with fructose and glucose making up 28% and 15%, respectively. Although Krishnamurthy *et al.* (1971), Lakshminarayana (1973; 1975) and Shashirekha and Patwardhan (1976) reported a simultaneous increase of glucose, fructose, and sucrose during ripening, Vazquez-Salinas and Lakshminarayana (1985) observed a gradual reduction in glucose and fructose and a continuous increase of sucrose during ripening in 'Haden', 'Irwin', 'Kent' and 'Keitt' mangoes. Medlicott and Thompson (1985) and Vazquez-Salinas and Lakshminarayana (1985) identified the main reducing sugar as fructose, while Selvaraj *et al.* (1989) reported that glucose is predominant. Sucrose content increases during ripening as a result of starch hydrolysis from increased amylase activity (Mattoo and Modi, 1969a; Fuchs *et al.*, 1980; Tandon and Kalra, 1983). The high activities of sucrose synthase and invertase in the mesocarp during ripening indicate active sucrose metabolism (Kumar *et al.*, 1994) and sucrose synthase activity increases about 10x during the phase of rapid sucrose accumulation (Castrillo *et al.*, 1992).

Organic acids decrease during maturation and ripening of mango fruit (Table 22.1). The predominant acids in mature mango fruit are citric, succinic, malic, and tartaric acids, citric acid being the most dominant and tartaric acid the lowest (Medlicott and Thompson, 1985). Citric acid content increases steadily during fruit development in 'Irwin' mangoes, reaching a maximum at the beginning of the endocarp-hardening period, and then decreases steadily (Ito

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et al., 1997). The predominant organic acids in 'Keitt' mango are citric and malic acids, but tartaric, oxalic, ascorbic and α–ketoglutaric acids also are present, and the initial loss in acidity is due to a substantial loss in citric acid and a small loss in malic acid (Medlicott and Thompson, 1985). Citric acid is the major organic acid in 'Badami' mango but malic and succinic acids are also present (Shashirekha and Patwardhan, 1976). In general, citric and succinic acids decrease during ripening while malic acid shows different changes with different cultivars (Lizada, 1993).

Fruit softening and cell wall changes are noticeable changes associated with mango fruit ripening. Softening of mango fruit is characterized by increased solubility of cell wall pectins (Nasrijal, 1993). In general, water-soluble polysaccharides increase during ripening (Brinson *et al.*, 1988), but water- and alkali-soluble pectins decline in 'Keitt' mangoes, and ammonium oxalate-soluble pectins increase as the fruit become soft (Roe and Bruemmer, 1981). There is an overall loss of galactosyl and deoxyhexosyl residues during mango fruit ripening, the latter indicating degradation of the pectin component of the wall (Muda *et al.*, 1995). The loss of galactose appears to be restricted to the chelator soluble fraction of the wall pectin, while loss of deoxyhexose seems to be more evenly distributed among the pectin. Pectinesterase (PE), which catalyses the deesterification of methyl groups from acidic pectins, has been detected in ripening mangoes (Ali *et al.*, 1995; Abu-Sarra and Abu-Goukh, 1992). Physiological maturity in ripened mangoes is associated with lower PE activity (Van Lelyveld and Smith, 1979) and peel has higher PE activity than pulp (Ashraf *et al.*, 1981). Endo-polygalacturonase (endo PG), which is responsible for degrading the 1–4-linked galacturonic acid residues, occurs in ripening fruit (Abu-Sarra and Abu-Goukh, 1992). Enzymatic and/or non-enzymatic processes, in addition to PG activity, are involved in the extensive softening of fruit (Mitcham and McDonald, 1992). Other cell wall hydrolases can be detected in ripening fruit, i.e., cellulases (Abu-Sarra and Abu-Goukh, 1992), ß-galactosidase (Ali *et al.*, 1995), galactanase (Ali *et al.*, 1990) and xylanase (Ali *et al.*, 1990). Ripening in mangoes, as characterized by decreased tissue firmness, is initiated in inner mesocarp tissue close to the seed, and progresses outward (Lazan *et al.*, 1993). Pectin solubilization in inner and outer mesocarp tissues is comparable, but it begins earlier in the inner than in the outer mesocarp (Lazan *et al.*, 1993). The outer mesocarp of 'Keitt' mangoes remains firm longer than 'Tommy Atkins', and the inner is softer than the outer mesocarp at each stage of ripening in both cultivars (Mitcham and McDonald, 1992). Cell wall neutral sugars, particularly arabinosyl, rhamnosyl and galactosyl residues, decrease with ripening in both cultivars. 'Keitt' has more loosely associated, chelator-soluble pectin, accumulates more soluble polyuronides and retains more total pectin at the ripe stage than 'Tommy Atkins'. The two cultivars have similar PG activity, which increases with ripening. The amount and molecular weight of cell wall hemicellulose decreases with ripening in both cultivars. Galactose is the only cell wall neutral sugar to show a significant decrease during ripening of 'Sensation' mangoes (Seymour *et al.*, 1990). Losses of neutral sugars can be due to hydrolysis of galactans and arabinogalactans by ß-galactosidase

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having galactanase activity. ß-galactosidase activity shows a parallel increase to tissue softening during ripening. The close correlations between changes in ß-galactosidase during ripening, and between changes in ß-galactosidase activity with tissue softening, and increased pectin solubility and degradation suggest that ß-galactosidase has an important role in cell wall pectin modification and mango fruit softening during ripening (Ali *et al.*, 1995).

Several postharvest treatments such as refrigeration, packaging, waxing and coatings, and MA/CA, can retard mango fruit softening and activity of PE (Nasrijal, 1993). Calcium infiltration or dipping of ‘Haden’ mangoes extended their storage life by one week (Zambrano and Manzano, 1995). Postharvest vacuum application of Ca to mango has also been tried (Yuen *et al.*, 1993). Vacuum (300 mm Hg) infiltration of 1–4% calcium chloride ($CaCl_2$) into ‘Amrapali’ and ‘Deshehari’ mangoes ripened at 25 °C inhibited PG activity, while ethylene treatment (1 μL L^{-1}) markedly increased its activity (Reddy and Srivastava, 1999). Pressure (115 kPa for 2 min) or vacuum infiltration (32 kPa) with 1–8% $CaCl_2$ delayed ripening of ‘Kensington Pride’ mangoes by 12 or 8 days, respectively (Yuen *et al.*, 1993). However, it has been reported that vacuum infiltration of $CaCl_2$ causes some peel injury, which can be reduced by increasing the temperature of the fruit flesh or the $CaCl_2$ solution during pressure infiltration, by packaging the fruit in sealed polyethylene during pressure infiltration, and by packaging the fruit in sealed polyethylene bags or cling or shrink wraps after $CaCl_2$ treatment (Yuen *et al.*, 1993). Calcium chloride infiltration of ‘Keitt’ mangoes reduced ethylene production, respiration rate and the incidence of decay (van Eeden, 1992).

Mango skin colour is important for the perception of overall quality (González-Aguilar *et al.*, 2001), and for determining the appropriate maturity for harvesting (Jha *et al.*, 2007), processing (Mahayothee *et al.*, 2004) and consumption (Jha *et al.*, 2007). The loss of green colour and the development of the optimum skin colour are signs of mango fruit ripening in many mango cultivars, and define quality (Plates XXXVIII and XXXIX). Depending on the cultivar, skin colour can change from dark to olive green; sometimes reddish, orange-yellow or yellowish hues appear from the base colour. Some cultivars develop a reddish blush, which has been attributed to anthocyanins. In yellow cultivars, carotenoids and xanthophylls are the predominant pigments. The anthocyanin paenoidin-3-galactoside occurs in the skin of some cultivars (Proctor and Creasy, 1969). During fruit ripening, chlorophyll concentration decreased substantially in ‘Keitt’, while carotenoid concentration increased and anthocyanin decreased gradually in ‘Tommy Atkins’ (Medlicott *et al.*, 1986). In ‘Keitt’, a substantial loss of chlorophyll in the peel occurs after the fruit begin to soften. Peel colour is not an adequate maturity index, since the fruit is already soft when the colour change occurs. ‘Tommy Atkins’ mangoes develop more red and yellow pigmentation in the peel and mesocarp than ‘Keitt’ (Mitcham and McDonald, 1992). Variation with respect to pigment types and quantities is due to cultivar differences, geography and climate, different maturity stages, and treatments after harvest; however, discrepancies in results are probably due to different analytical procedures. As mentioned earlier, mango fruit pulp

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contains high concentrations of carotenoids (up to 9 mg 100 g^{-1}), causing the development of an intense yellow to orange colour, and the fruit is a good source of vitamin A. The pulp carotenoid level is cultivar-dependent. 'Tongdum' mangoes, which ripen without changing colour, have three times more chlorophyll and slightly more ß-carotene in the peel and have higher rates of ethylene production compared with 'Nam Dok Mai' mangoes, which change from green to yellow upon ripening (Ketsa *et al.*, 1999). Activities of chlorophyllase and peroxidase in the peel of ripe 'Tongdum' fruit are about half of that in 'Nam Dok Mai' fruit. Therefore, changes in the peel of ripe green mangoes are due to either or both a lower activity of chlorophyllase or peroxidase activity and are not a result of low ethylene production.

The phenolic content of mangoes is high in the early stages of development, then decreases and remains fairly steady during ripening (Lakshminarayana *et al.*, 1970). This is associated with loss of astringency (Selvaraj and Kumar, 1989). The peel of mango fruit has a higher phenolic content than the pulp at all stages of fruit development (Jain, 1961; Lakshminarayana *et al.*, 1970). Polyphenol oxidase (PPO) catalyses the oxidation of mono- and diphenols to *o*-quinones, which polymerize to produce brown pigments. PPO activity increases slightly from harvest maturity to the half-ripe stage and then declines in 'Banganapalli', 'Dasheri', 'Fazli' and 'Langra' mangoes, and decreases in 'Alphonso', 'Suvarnarekha' and 'Totapuri' mangoes (Selvaraj and Kumar, 1989). PPO isolated from 'Haden' mango was found to be active towards the o-diphenolic compounds, showing higher activity in the presence of catechol, followed by chlorogenic acid, but not with monophenols (Park *et al.*, 1980).

Ripe mangoes contain more than 300 volatiles (Pino *et al.*, 2005), but not all of them are odour-active and thus do not contribute significantly to aroma. Studies have identified the volatiles of mango, but not their aromatic activity. The predominant volatiles in some cultivars are monoterpenes and sesquiterpenes (Pino *et al.*, 2005), as well as lactones and some fatty acids (Wilson *et al.*, 1990). However, there is no indication of the presence of a single flavour impact component (Engel and Tressl, 1983). Some mango cultivars have a peach-like flavour that may be related to the presence of lactones, which contribute to the flavour of peach fruit (Wilson *et al.*, 1990). MacLeod *et al.* (1988) detected four lactones in 'Kensington Pride' that are also the major volatiles of peach. Monoterpene hydrocarbons represent about 49% (w/w) of the total volatiles in 'Kensington Pride', with α-terpinolene being the most abundant (26%) and 16 esters representing 33% (MacLeod *et al.*, 1988). The esters, together with some of the lactones, contribute to the flavour of 'Kensington' mangoes.

Tree-ripe 'Tommy Atkins' mangoes produce higher levels of all aroma volatiles except hexanal than do mature-green fruit (Bender *et al.*, 2000a). Both mature-green and tree-ripe mangoes stored in 25 kPa CO_2 tend to have lower terpene (especially p-cymene) and hexanal concentrations than those stored in 10 kPa CO_2 and air-stored fruit. Acetaldehyde and ethanol levels tend to be higher in tree-ripe mangoes held in 25 kPa CO_2 than in those from 10 kPa CO_2 or air storage, especially at 8 °C. Inhibition of volatile production by 25 kPa CO_2 is greater in mature-green than in tree-ripe mangoes, and at 8°C compared to 12°C for tree-ripe

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fruit. However, aroma volatile levels in tree-ripe mangoes from the 25 kPa CO_2 are equal to or greater than those in mature-green fruit treatments. Atmospheres that prolong mango shelf life by slowing ripening processes can allow tree-ripe mangoes to be stored or shipped without sacrificing their aroma quality.

Lipid content of the pulp is correlated with the flavour characteristics of some mango cultivars (Gholap and Bandyopadhyay, 1976). The ripening of 'Alphonso' mangoes at ambient temperature is accompanied by a sharp increase in triglyceride content, together with the development of a strong aroma and flavour (Gholap and Bandyopadhyay, 1976), but ripening at 10°C results in a bland aroma and flavour (Bandyopadhyay and Gholap, 1973a,b). 'Totapuri' mangoes, a bland cultivar, showed no change in the development of aroma or in the pulp lipid content (Gholap and Bandyopadhyay, 1975a,b). During ripening at ambient temperature, palmitoleic acid content is higher than that of palmitic acid in 'Alphonso', whereas ripening at low temperature does not affect the proportions of these two fatty acids (Bandyopadhyay and Gholap, 1973b). The relative proportions of palmitoleic and palmitic acids in 'Totapuri' mango pulp were found to be constant irrespective of the ripening conditions (Gholap and Bandyopadhyay, 1975b). Gholap and Bandyopadhyay (1980) suggested that the relative contents of palmitic and palmitoleic acids determine the flavour quality of mango fruit.

22.2.4 Manipulation of postharvest physiology by molecular biology

Mango fruit harvested before the fruit are fully mature are unable to achieve the full complement of flavour and aroma after harvest compared with fruit harvested at a fully mature or ripening initiated stage of development. The presence of ethylene is required for the progression and completion of mango ripening. Thus, strategies for prolonging the postharvest life and maintaining postharvest quality of mango have been focusing on reducing the effects of ethylene. This situation provides an excellent opportunity to utilize genetic transformation to improve mango postharvest quality by manipulating the role of ethylene. Cruz-Hernandez *et al.* (1997) transformed 'Hindi' mango with mango ACC oxidase and ACC synthase in the antisense orientation. A cDNA that codes for mango ACC oxidase was also isolated and characterized by Zainal *et al.* (1999). Suppression of mango ethylene biosynthesis should allow harvesting of advanced maturity fruit that contain high levels of sugars and possess enhanced capacity to produce ripe aroma volatiles after exposure to exogenous ethylene. Progression of ripening in such fruit can be easily halted at the most desirable and convenient time by simply removing exogenous ethylene. A cDNA homologue of the ethylene receptor gene ETR-1, referred to as METR1, which codes for a polypeptide of 802 amino acids with a predicted 89 kDa MW has been isolated (Gutierrez-Martinez *et al.*, 2001). Two or more ETR homologues exist in mango. The level of METR1 mRNA in the mesocarp increases transiently during wounding. Repression of genes involved in ethylene action in mango fruit should result in ethylene-insensitive fruit that are minimally affected by exposure to ethylene in the postharvest environment, resulting in better control of ripening and senescence to maintain mango

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postharvest quality. Internal breakdown in mango fruit is essentially a problem of premature ripening; the longer the harvest of susceptible varieties is delayed, the greater the incidence of internal breakdown. Using molecular approaches to reduce ethylene production and action in mature fruit could reduce internal breakdown or premature ripening and lead to better quality. Another approach to mitigating internal breakdown would be to target genes involved in the maintenance of cell wall integrity. Vasanthaiah *et al.* (2006) demonstrated differential expression of several genes in tissue showing internal breakdown symptoms compared with healthy tissue. They suggested that oxidative stress may be one of the causes of the disorder. Sane *et al.* (2005) isolated and characterized an ethylene-dependent a-expansin gene, MiExpA1, which is correlated with softening in mango. Expression of MiExpA1 increases with the progression of ripening and treatment with 1-MCP inhibits both ripening/softening as well as MiExpA1 transcript and protein accumulation. A pectate lyase homologue from ripening mango (MiPel1) has been cloned (Chourasia *et al.*, 2006). A progressive increase in transcript accumulation was observed during ripening but expression was delayed significantly in fruit maintained in air without exogenous ethylene. The expression was specific to fruit and was triggered only during ripening. Increased transcript accumulation during ripening was associated with pectin solubilization. Pectate lyase may be closely associated with pectin degradation and have an important role in mango softening.

22.3 Maturity and quality components and indices

Mango quality at arrival, especially in import markets, varies widely among different lots (Medlicott *et al.*, 1988). The supply of high-quality fruit requires the selection of uniformly ripened fruits. The frequent need to transport fruit over long distances has necesitated harvesting mango fruit at less-than-optimal maturity, which has resulted in poor quality fruit entering the market (Medlicott *et al.*, 1988). There are many factors that can influence the maturity and quality of the fruit. Fruits on the same tree may vary significantly in maturity due to uneven or prolonged flowering. In addition, variation in maturity between fruit can be influenced by where fruit hang on the tree. In the southern hemisphere, fruit on the northern side of the tree have been reported to mature more quickly than fruit on the southern side (Oosthuyse *et al.*, 1995). These factors, in addition to the great diversity of cultivars grown in the world, make maturity at harvest very much dependent on cultivar, region, environmental conditions, type and purpose of market, etc.

Maturity at harvest determines both the postharvest life of the fruit and its quality. Fruit harvested before optimum maturity will either never ripen or never reach optimum quality. Less mature fruit are more sensitive to CI and may fail to ripen adequately. Mangoes harvested at the mature and half-mature stages ripen to good-quality fruit (Medlicott *et al.*, 1990; Seymour *et al.*, 1990). Fruit harvested after optimum maturity will have a shorter postharvest life. Fruit harvested medium-ripe or ripe and stored for a short period showed lower contents

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of sugar and carotenoids (Lakshminarayana, 1975). Over-mature fruit is highly susceptible to mechanical damage such as bruising, to decay and water loss, and to defects like jelly seeds or jelly pulp, resulting in quality deterioration (Yahia, 1998b; 2005). Therefore, suitable maturity indices for harvesting are very important in order to minimize the qualitative and quantitative losses.

Several physical, physiological and chemical parameters can be considered to define the maturity stage. Physical methods include softness of cheeks, peel colour, development of shoulders and specific gravity (Yahia, 1998b; 2005). While immature fruit have a flat shape in profile, with shoulders that slope down below the pedicel insertion, mature fruit have full cheeks and raised shoulders at the stem end. These factors are very useful, but their application depends on type of mango, region of cultivation, and type of market and consumers. Age of the fruit is also considered as a simple method to confirm maturity, which is calculated from induction, full bloom and fruit set. Generally, harvest maturity in mango can be reached after about 12 to 16 weeks from fruit set; however, days from full bloom is the most recommended measure, because this can be implemented as a standardized factor (Yahia, 1998b). The age of fruit (days) at a certain harvest maturity based on full bloom or fruit set varies according to different cultivars and geographical regions. Table 22.2 shows examples of the use of computation in different countries in ASEAN.

Mango fruit accumulates dry matter during fruit development and becomes denser as it matures, and therefore specific gravity has been considered as a possible maturity index. It generally ranges from 0.97 to 1.04, but it does not

Table 22.2 Examples of the use of computation in different ASEAN countries

Cultivar	Age (days)	Computation	Country
'Arumanis'	90	Full bloom	Indonesia
'Arumanis'	91	Fruit set	Malaysia
'Blencong'	86	First bloom	Indonesia
'Carabao'	84	Full bloom	Philippines
'Carabao'	116	Flower	Philippines
'Cempora'	101	First bloom	Indonesia
'Golek'	78	Full bloom	Indonesia
'Golek'	84	Fruit set	Malaysia
'Kam Daeng'	71	Full bloom	Thailand
'Malgoa'	108	First bloom	Indonesia
'Malgoa'	112	Fruit set	Malaysia
'Nam Dork Mai'	100	Full bloom	Thailand
'Nam Dork Mai'	102	Full bloom	Philippines
'Nam Dork Mai'	93	Fruit set	Thailand
'Nang Klarngwun'	115	Full bloom	Thailand
'Tok Boon'	105	Fruit set	Malaysia
'Tongdum'	102	Full bloom	Thailand
'Yampulu'	101	First bloom	Indonesia

Source: Yahia (1998b)

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contribute adequately to determining fruit maturity, and therefore it is not used commercially (Yahia, 1998b).

During fruit maturation soluble solids content (SSC) tends to increase while titratable acidity (TA) decreases. According to Tharanathan *et al.* (2006) TA increased from the sixth to the tenth week after fruit set, and then with increase in fruit maturity a decline was noted. However, neither SSC nor TA is used as a commercial maturity index for mangoes, although SSC may complement other indices such as shoulder formation and flesh colour.

Loss of green skin colour is one of the common characteristic of ripening in many mango cultivars, and it is an important fruit quality parameter that affects consumer acceptance and preference. The change from dark green to olive green or reddish or orangish yellow or yellow that forms a base colour is a noticeable change during ripening. Some cultivars show reddish blue skin colour due to the presence of anthocyanins (Tharanathan *et al.*, 2006). These skin colour changes are due to the disappearance of chlorophyll and the appearance of other pigments (carotenoids and/or anthocyanins). Carotenoids are the predominant pigments in yellow cultivars, and presence of the anthocyanin phenondin-3-galacytosa has been reported in the skin of some mango cultivars. However, skin colour is not considered as an adequate maturity index because the colour change due to loss of chlorophyll is commonly observed after the fruit has started to soften, and also because skin colour does not change in some cultivars, and the changes are not unifom in several other cultivars. Skin colour development is greatly influenced by the fruit position on the tree and by fertilizer application practices, among other factors.

However, flesh colour changes are uniform when fruit advances in maturity stages (Figures 22.2 and 22.3), and can serve as an adequate maturity index. Although it is a destructive index, it is used as a maturity index in several producing regions, because it is consistent (Yahia 1998b; 2005). Flesh colour was observed to show consistent performance in several mango cultivars such as 'Tommy Atkins', 'Keitt', 'Kent' and 'Haden'. Carotenoids are responsible for the attractive flesh colour, and at advanced maturity the flesh is usually yellow to orange (Medlicott *et al.*, 1986; Ornelas-Paz *et al.*, 2008).

Mainly due to the diversity of cultivars and growing conditions, it has not been easy to establish standard maturity indices for mangoes,, but it is essential to develop them for a particular cultivar, growing region and for local or export markets. Maturity indices for 'Tommy Atkins', 'Keitt', 'Kent' and 'Haden' are based on position and thickness of the shoulders and colour of the flesh closer to the skin (Yahia, 1998b; 2005). The fully mature fruit of these cultivars will show a completely formed shoulder with a depression around the peduncle, firm and green in colour.

There are a number of promising technologies for non-destructive assessment of mango maturity and quality. The development of a non-destructive flesh colour sensor for mango would help in correlating with indices such as shape, size and flesh colour in order to establish better estimation of maturity stage at harvest (Slaughter, 2009). Near-infrared (NIR) technology was tested to assess dry matter in 'Kensington' mangoes, and to establish relationships between reflectance

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spectra and quality parameters in 'Tommy Atkins' mangoes (Schmilovitch *et al.*, 2000). A technique was reported for the estimation of mango maturity based on ultrasonic properties of the fruit (Mizrach *et al.*, 1999). The analogue signal of an ultrasonic wave passing through whole mango fruit flesh was transmitted and received by means of ultrasonic probes in contact with the fruit peel. Mizrach et al. (1999) examined the firmness and some of the internal physiological indices in the tissue of mango fruit and found them to be well coordinated with ultrasonic non-destructive measurement parameters such as ultrasonic wave velocity and attenuation.

High quality mangoes at destination are sweet, with firm, juicy, tender flesh, aromatic and flavourful, and fibre content should be minimal. Acceptable quality scores for 'Tommy Atkins' mangoes were considered as pulp rupture force of 0.5–1.0 kg, greater than 9.5% soluble solids, pH 4.0, and pulp and peel colour score of 3.0 (Medlicott *et al.*, 1988). Pulp rupture force value of less than 0.5 kg was indicative of over-ripe fruit.

Mango for the export market must comply with requirements of consumers and with quality standards of the importing market in terms of size, colour, appearance, absence of defects, ripening stage, uniformity, absence of insects and diseases, phytosanitary regulations, etc. Uniformity of quality is an important factor for export fruit. The fruit must arrive at the market at an optimum ripening stage that can allow reasonable shelf life for retail marketing. Import markets have established quality standards. Some of the important quality standards developed include: Codex Alimentarius: Worldwide Codex Standard for Mangoes, Codex Stan 184–1993; for Mexico: NOM-FF-58-1985, Mexican Official Standard for Mango (Norma official Mexicana); and for Europe: UN/ECE standard FFV-45, Concerning the marketing and commercial quality control of mangoes.

In general, import markets require that mango fruit on arrival:

- are physiologically mature;
- show 30 to 50% development of colour (and in the case of red cultivars, a significant amount of red area must have developed in the fruit shoulder);
- are firm;
- have a minimum of 10% sugar;
- are of uniform shape;
- are free from diseases, insects, latex stains, soil burns and mechanical injury;
- meet specific size and weight requirements.

22.4 Preharvest factors affecting fruit quality

Many factors, especially environmental conditions, can influence mango development and influence fruit quality. The same cultivar can acquire different characteristics in different growing conditions (Hofman *et al.*, 1997). Even in the same region, different environmental conditions in different years can affect maturity and quality of the fruit. For example, growers in the Philippines are accustomed to

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harvest mangoes after 100–110 days from induction during April to June, but fruit picked in January to March are picked after 120–125 days (Yahia *et al.*, 2006a).

22.4.1 Light

Light is important for photosynthesis, which determines the amount of assimilates (carbohydrates) available for translocation to the developing fruit. Increasing the leaf:fruit ratio increased mango fruit size and dry matter content (Simmons *et al.*, 1998). Another important effect of light on the fruit is on the development of anthocyanin pigments responsible for colours ranging from red to blue. The intensity of light in a specific region will determine the quality of the fruit from the standpoint of colour. The differences in light intensity between mango growing regions can produce fruit of different colours.

22.4.2 Temperature

Temperature is a very important factor that influences fruit maturity and quality. Ovules in young mango fruit may abort at both low (<12°C) and high (>44°C) temperatures (Yahia *et al.*, 2006a). Temperature can influence the suitability of a growing region for mango cultivation, and also the harvest period and quality of the fruit. For example, mango can be harvested in January–February in the southern part of Mexico, but not until June–August in the northwestern part (Yahia *et al.*, 2006a).

The minimum temperature (base temperature) at which mango fruit will not develop normally is reported to be 17.9°C (Yahia, 2005). Heat units, which are calculated from the sum of the temperature units (degree days) in excess of the base temperature over the growing season, have been calculated in some countries for mango. In the Philippines it has been found that 'Carabao' mango fruit in different regions reach maturity after 1000 heat units, even though this is reached at different periods in different regions.

22.4.3 Rainfall and irrigation

The amount and distribution of rainfall not only determines the suitability of the region for mango growing, but also influences the maturation and quality of the fruit. Mango growing is generally successful when the annual rainfall ranges between 75 and 350 cm, there is no water-logging, and the rain does not fall during flowering, fruit set, or fruit development (Yahia, 2005). Conditions are ideal for mango when at least 4 months of dry weather occur between flowering and harvest. In this period and at other times when there is no rainfall, irrigation is needed. Prolonged moisture stress can result in late flowering and small fruit. The critical period for fruit development is during the first 4 to 6 weeks when cell division and cell wall synthesis occur. Singh *et al.* (1998) showed that maintaining soil moisture at 60% capacity or higher improved fruit retention, fruit quality, and yield. Irrigation may be withheld as fruit approach maturity in order to improve sugar content.

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22.4.4 Fertilization

Mango trees, especially young trees, need an adequate supply of nutrients for an adequate rapid growth, flowering, and fruiting (Yahia, 2005; Yahia *et al.*, 2006a). Excess application of nitrogen increases the leaf:fruit ratio and can adversely affect the colour of mature fruit. Increasing the leaf:fruit ratio from 30 to 120 increased fruit size and increased shelf life at the middle ratio, but increased the incidence and severity of disease at the highest ratio (Simmons *et al.*, 1998). The addition of potash to trees with excess nitrogen can improve the colour and flavour of the fruit. Potash deficiency is associated with small fruit of poor quality, and high potash levels are associated with an increase in physiological breakdown of the fruit. However, this problem has also been attributed to calcium deficiency. The high potash level can result in a lack of balance between potassium and calcium in the tree and in the fruit. The requirement of mango for phosphorus is usually low, and the deficiency for such element is usually uncommon. Deficiency of boron and calcium adversely affect the keeping quality of mango fruit. Nutrient imbalance can cause the development of fruit disorders such as internal breakdown (Yahia, 2005).

22.4.5 Chemicals

Pests and disease control

Insects and diseases result in loss of yield and deterioration of quality, and thus adequate control is essential. Preharvest pest control contributes very significantly to yield and postharvest quality, but may adversely influence quality from the standpoint of residue content. Integrated pest management (IPM) strategies are essential to control pests, but at the same time reduce the use of pesticides. Prediction of diseases, based on the monitoring of environmental conditions, can significantly reduce the use of pesticides. Biological control is becoming important in reducing insect and disease population, and thus reducing the use of pesticides.

Growth regulators

Very little work has been done, and therefore there is little application of growth regulators in mango. Following pre-harvest application of ethephon (2-chloroethylphosphonic acid) at 50–200 ppm to 'Carabao' mango at 78 days from induction, fruit harvested one week later had increased SSC and less acidity (Yahia, 2005).

22.4.6 Bagging

Individual bagging is used in some regions to protect fruit from insects and diseases. Fruits are commonly bagged at 55–60 days from full bloom or after the period of heavy fruit drop, but fruit can also be bagged earlier if early floral induction has occurred. Bagging reduces insects, anthracnose and stem-end rot, and thus affects fruit quality and may also affect fruit maturity (Yahia, 2005).

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22.5 Postharvest handling factors affecting quality

22.5.1 Temperature management

Temperature is the most important factor affecting postharvest life and quality of fresh horticultural crops. Low temperature is needed to reduce metabolic activity, delay ripening and senescence, reduce water loss, prevent or reduce disease and insect activity, and thus maintain postharvest quality and increase postharvest shelf life. However, mango, like almost all tropical fruits, is very sensitive to low temperature. High temperature is used to ripen the fruit and to control insects and diseases, but the exposure of mango to longer periods of high temperature can cause fruit damage (Yahia, 2005). Mango fruit usually remain green at temperatures of 28°C or higher and do not ripen when maintained at temperatures of 33°C or higher for prolonged periods (Yahia, 2005).

22.5.2 Physical damage

Mangoes are susceptible to physical damage at virtually every part of the postharvest handling chain, and reduction/elimination of physical/mechanical injury is essential to reduce losses in quality and in postharvest life (Yahia, 2005). Even green mangoes can fracture internally if dropped from a height during the harvest operation. Careful transport from the field is necessary to avoid additional injury. Packinghouse handling allows washing plus better selection and packing according to size compared to other handling and packing systems. Strong shipping containers with internal dividers help protect mangoes from damage during loading, shipping, and unloading operations, and as the fruit ripen and soften. The types of physical damage that may occur to mangoes include scuffing, along with compression, vibration, and impact bruising (Yahia, 2005). Scuffing occurs when fruit surfaces are abraded by stems of other fruit, the sides of rough or dirty picking containers, dirty packing line conveyors and worn or stiff packing line brushes. Mangoes can also develop scuffing when vibration in transit allows individual fruit to rub against each other. Dropping, compression and vibration cause bruising to the flesh of mango fruit, which shows up internally as discoloured, water-soaked areas. Ripe fruit are more susceptible to bruising and thus require better packaging. Mechanical injury can be the cause of several other problems, including the increase of respiration rate and ethylene production, increasing the loss of water, facilitating the attack and penetration of disease causal agents, etc. The reduction/elimination of mechanical injury is essential to reduce losses in quality and in postharvest life.

22.5.3 Transpiration and water loss

Mangoes are not very susceptible to water loss compared to other crops, but may show shrivel symptoms over time if humidity levels are not properly managed. Mango water loss, through stomata, lenticels and other openings, decreases fruit weight, resulting in shrivelling, and may further reduce quality by causing poor

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colour development and uneven ripening (Yahia, 2005). Water loss is greatly influenced by temperature and relative humidity (RH) in the environment. With constant RH and air movement, water loss increases significantly with any increase in temperature. Transpiration rate is influenced by cultivar and ripeness stage. It is correlated with skin thickness, morphological structure, epidermal cells and surface wax coating. For example, waxes usually develop on the epidermis of fruit in the later stages of fruit development and thus it is common for fruit harvested early to shrivel faster compared with those harvested at a more advanced stage of development (Yahia *et al.*, 2006a). Mangoes should be kept in an environment of about 85 to 90% RH. Slow cooling, such as placing warm mangoes directly into a refrigerated area, will promote water loss because of the large gradient in water concentration between the fruit and the relatively dry, cold air. The area near the stem scar is more susceptible to water loss than the rest of the fruit and thus is usually the first to show shrivelling. Scuffed areas on the surface of the fruit also collapse and shrivel from water loss.

22.5.4 Atmosphere

As mentioned previously, the initiation of ripening in mangoes can be delayed by changing the composition of the storage atmosphere so that the oxygen (O_2) level is reduced and the carbon dioxide (CO_2) level is raised by using modified (MA) or controlled atmospheres (CA). Long-term marine shipping in MA and CA has been used for transit from several countries (Yahia, 1993; 1994; 1997; 1998b; 2008). Research results are very contradictory due to the different cultivars and maturity stages of mangoes used, different atmospheres implemented, and lack of experimental controls. Optimum conditions for prolonged shipping or storage are reported to be 3–5 kPa O_2 and 5–10 kPa CO_2, which can delay ripening, but the benefits are not very significant (Yahia, 1998b). Use of CA and MA would most likely be beneficial in delaying fruit ripening during marine transport for 2 weeks or more.

Bender *et al.* (2000b) determined the tolerance of preclimacteric 'Haden' and 'Tommy Atkins' to reduced O_2 levels for storage times in typical marine shipments. They reported that mangoes can tolerate 3 kPa O_2 for 2–3 wks at 12–15°C and that tolerance of low O_2 decreases as mangoes ripen. All low O_2 treatments reduced mature-green mango respiration; however, elevated ethanol production occurred in 2 and 3 kPa O_2 storage, with the levels two to three times higher in 'Tommy Atkins' than in 'Haden'. 'Haden' fruit at the onset of the climacteric accumulated ethanol in 4 kPa O_2 and produced 10–20x more ethanol in 2 and 3 kPa O_2 than preclimacteric fruit. There were no visible injury symptoms, but off-flavour developed in mature-green fruit at 2 kPa O_2 and in ripening initiated fruit at 2 and 3 kPa O_2. Ethanol production was not affected by storage in 25 kPa CO_2. Ethylene production was reduced slightly by low O_2; however, 'Haden' fruit also showed a residual inhibitory effect on ethylene production at 2 or 3 kPa O_2 storage, while 'Tommy Atkins' fruit stored in 2 kPa O_2 produced a burst of ethylene upon transfer to air at 20°C. Fruit firmness, total sugars, and starch levels

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did not differ among treatments, but 2, 3 or 4 kPa O_2 and 25 kPa CO_2 maintained significantly higher acidity than 5 kPa O_2 or air. The epidermal ground colour responded differently to low O_2 and high CO_2 in the two mango cultivars. Only 2 kPa O_2 maintained 'Haden' colour better than air, while all low O_2 levels maintained 'Tommy Atkins' colour equally well and better than air. High CO_2 was more effective than low O_2 in maintaining 'Haden' colour, but had about the same effect as low O_2 on 'Tommy Atkins'.

Properly selected atmospheres, which prolong mango postharvest life by slowing ripening processes, can allow tree-ripe mangoes to be stored or shipped without sacrificing their superior aroma. Mature-green (MG) and tree-ripe (TR) 'Tommy Atkins' mangoes were stored for 21 days in air or in a CA (5 kPa O_2 + 10 kPa or 25 kPa CO_2) at 12°C (MG) and at either 8 or 12°C (TR) (Bender *et al.*, 2000a). TR mangoes produced much higher levels of all aroma volatiles except hexanal than MG fruit after ripening for 2 days. Both MG and TR mangoes stored in 25 kPa CO_2 have lower terpene (especially p-cymene) and hexanal levels than those stored in 10 kPa CO_2 and air-stored fruit. Acetaldehyde and ethanol levels are higher in TR mangoes from 25 kPa CO_2 than in those from 10 kPa CO_2 or air storage, especially at 8°C. Inhibition of volatile production by 25 kPa CO_2 is greater in MG than in TR mangoes, and at 8°C compared to 12°C for TR fruit. Aroma volatile levels in TR mangoes from the 25 kPa CO_2 treatment are equal to or greater than those in MG fruit treatments.

Mangoes are very tolerant of insecticidal atmospheres, and thus a potential commercial application is feasible, especially in combination with other treatments, i.e., heat. 'Keitt' mango tolerated as low as 0.2 kPa O_2 and as high as 80 kPa CO_2 for up to 5 days without any injury upon ripening, although fermentative odours could be noted while the fruit were under atmosphere stress (Yahia, 1993; 1994; 1995; 1997; 1998a; Yahia and Ortega, 2000; Yahia and Tiznado, 1993; Yahia *et al.*, 1989; Yahia and Vazquez, 1993; Ortega and Yahia, 2000). Some other mango cultivars were later evaluated and were also very tolerant of extreme atmospheres (Yahia, 1998a; 2008). Storage of 'Keitt' mangoes in an insecticidal MA (0.03–0.26 kPa O_2, 72–79 kPa CO_2, balance N_2), and CA (0.2 kPa O_2, balance N_2) or 2 kPa O_2 + 50 kPa CO_2, balance N_2) for up to 5 days at 20 °C delayed fruit ripening as indicated by respiration, flesh firmness, and colour development (Yahia *et al.*, 1989; Yahia, 1993; Yahia and Tiznado, 1993; Yahia and Vazquez, 1993). The activity of phosphofructokinase, ADH and PDC was enhanced but activity of pyruvate kinase, succinate dehydrogenase and α-ketoglutarate dehydrogenase was unaffected. Although these atmospheres caused changes in glycolysis and tricarboxylic acid cycle, there was no indication of injury and the fruit ripened normally in air. Sensory evaluation conducted after fruit ripening showed no off-flavours, and there were no differences between fruit maintained in the MA or CA and those maintained continuously in air. 'Keitt' mango is therefore very tolerant of insecticidal atmospheres, and 5 days exposure is sufficient to control many insects (Rojas-Villegas *et al.*, 1996). Storage of 'Keitt' and 'Tommy Atkins' mangoes for 21 days at 12°C in an atmosphere containing 25, 45, 50, or 70 kPa CO_2 plus either 3 kPa O_2 or air induced ethanol

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production of 0.18 to 3.84 ml $kg^{-1}h^{-1}$ after transfer to air at 20°C for 5 days (Bender *et al.*, 1994). Atmospheres containing 50 or 70 kPa CO_2 caused fruit injury, and resulted in the highest ethanol production rates. The enclosure of 'Haden' and 'Tommy Atkins' mangoes in sealed 20-litre jars with an initial atmosphere of 90 kPa CO_2 in air or 97 kPa N_2 + 3 kPa O_2 for 24 h prior to storage delayed their ripening, and no injury was reported (Pesis *et al.*, 1994).

The quality of 'Keitt' mangoes was evaluated during storage for 6 days at 20°C in an extremely low O_2 (LO) CA (approx 0.3 kPa) before storage in modified atmosphere packaging (MAP) made from three low density polyethylene (LDPE) films with different gas permeability characteristics (Gonzalez-Aguilar *et al.*, 1997). Both LO and MA treatments delayed the losses of colour, weight and firmness. Fruit maintained good appearance with a significant delay of ripening. Mangoes are very tolerant of LO treatment; however, some MAP fruit developed a fermented taste after 10 and 20 days at 20°C. Short duration (6-day) storage of mangoes in LO did not otherwise have any deleterious effect on fruit quality during subsequent storage under MA or normal atmosphere. Properly selected atmospheres, which prolong mango postharvest life by slowing ripening, permit fruit to be shipped without sacrificing superior aroma.

Beaulieu and Lea (2003) studied the production of volatiles in heat-treated 'Keitt' and 'Palmer' mangoes to assess volatile and quality changes in stored fresh-cut mangoes prepared from firm-ripe (FR) and soft-ripe (SR) fruit, and to assess what effect MAP may have on cut fruit physiology, overall quality and volatile retention or loss. Subjective appraisals of fresh-cut mangoes based on aroma and cut edge or tissue damage indicated that most SR cubes are unmarketable by day 7 at 4°C. Both cultivars stored in MAP at 4°C have almost identical O_2 consumption, which is independent of ripeness. The CO_2 and O_2 concentrations measured for cubes stored in passive MAP indicate that the system is inadequate to prevent potential anaerobic respiration after 7 days storage.

Mango fruit wrapped in 0.08 mm thick polyethylene bags, with and without perlite-$KMnO_4$ and stored for 3 weeks at 10°C before treatment with ethylene were ripened to normal colour, texture and flavour (Esguerra *et al.*, 1978). Individually sealed 'Keitt' in LDPE and HDPE polyethylene films for 4 weeks at 20°C exhibited delayed ripening, reduced weight loss, and did not develop any off-flavours (Gonzalez *et al.*, 1990). The LDPE had a thickness of 0.010 mm and permeabilities of 700 cc O_2 $m^2hr^{-1}atm^{-1}$, and 0.257 g H_2O $m^2hr^{-1}atm^{-1}$. The HDPE film had a thickness of 0.020 mm and permeabilities of 800 cc O_2 $m^{-2}hr^{-1}atm^{-1}$, and 0.166 g H_2O $m^{-2}hr^{-1}atm^{-1}$. In a study to model MAP for mango, 'Keitt' fruit were individually vacuum packaged in LDPE film (24.5 mm thick, 25.0 g m^{-2}) and stored at 7°C/80–90% RH, 12°C/75–85% RH, 17°C/70–80% RH, 22°C/65–75% RH or 25°C/65–75% RH (Yamashita *et al.*, 1997). After mass transfer had reached steady state, respiration rates, moisture loss, permeability of peel and film to water vapour, and composition of atmosphere around the fruit were determined for 33 days. Daily rates of weight loss increased from 4.1 g kg^{-1} of fruit at 7°C to 10.9 g kg^{-1} at 25°C. Respiration rates also increased with storage temperature for both packaged and unpackaged mangoes, and were 21, 38 and

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43% less in packaged fruit at 12, 17 and 22°C, respectively. Permeability of peel was 600 times greater than that of the plastic film. The in-package CO_2 levels increased and O_2 decreased with time; concentration changes were greatest during the first 10–15 days of storage and were more marked at the higher temperatures. Experimental and calculated values for CO_2 levels differed by 29% depending on temperature. 'Tommy Atkins' mangoes individually sealed in heat shrinkable films and stored for 2 weeks at 12.8°C and then ripened at 21°C had less weight loss, but did not show differences in firmness, skin colour development, decay development or time to fruit ripening, and had more off-flavours than unwrapped fruit (Miller *et al.*, 1983). Polyethylene films used were: Clysar EH-60 film of 0.01 nominal thickness, Clysar EHC-50 copolymer film of 0.013 mm nominal thickness, and Clysar EHC-100 copolymer film of 0.025 mm nominal thickness. Individual mature fruit of the same cultivar were later sealed in Clysar EHC-50 copolymer film with 0.013 mm thickness, and Cryovac D955 with 0.015 thickness, and stored at 21°C and 85–90% RH (Miller *et al.*, 1986). The O_2 permeabilities of the films were 620 cm^3 24 hr^{-1} m^{-2} atm^{-1} and 9833 cm^3 24hr^{-1} m^{-2} atm^{-1}, respectively. Water permeability was 1.5 g 24 hr^{-1} m^{-2}, and 2.0 g hr^{-1} m^{-2} at 23°C, respectively. Fruit in MAP had less weight loss, but higher incidence of decay and off-flavour at soft ripeness than unsealed fruit. The authors concluded that there were no practical benefits from wrapping the fruit in these films and storage at 21°C or even at lower temperatures. 'Keitt' mangoes were individually sealed in LDPE films and in a heat-shrinkable copolymer (Cryovac D-955) film with non-sealed mangos as the control and stored for up to 5 weeks at 12°C, 17°C or 22°C (Yamashita *et al.*, 1999). MAP reduced the rate constant of vitamin C degradation at all temperatures and vitamin C content of individually packaged mangoes was less affected by storage temperature than the control. Values for Q10 were 1.3 and 1.0 for mangoes wrapped with the heat-shrinkable copolymer and the LDPE films, respectively, and 2.8 for the non-sealed control.

The combined effect of hot benomyl (1000 ppm) solution at 55°C for 5 min and seal packaging in 0.01 mm PVC extended the storage life of mature-green 'Nam Dok Mai' mangoes stored at 13°C (Sornsrivichai *et al.*, 1992). Fruit quality was not affected by film packaging after 4 weeks, but fruit showed inferior quality after 6 weeks. The inhibition of carotene pigmentation in the peel of this cultivar may be related to O_2 concentration inside the package and not to CO_2 concentration (Yantarasri *et al.*, 1994). At least 16 kPa O_2 is essential for development of peel colour to the marketable stage (greenish). 'Kensington' mangoes treated with heated benomyl (0.5 g L^{-1} at 51.5°C for 5 min) and sealed in polyethylene bags (0.04 mm thickness) for various durations at 20°C, had off-flavour and lacked normal skin colour when ripened, but ripened satisfactorily in perforated bags (Chaplin *et al.*, 1982). The postharvest life of these fruit was not consistently longer than the control. The CO_2 concentration in the bags was >20 kPa while the O_2 concentration was <5 kPa. The incidence of off-flavours was reduced by including C_2H_4 absorbent blocks in the bags. The authors concluded that 'mangoes cannot be stored satisfactory at ambient temperature by such technique'; however, Stead and Chithambo (1980) reported that fruit ripening at 20–30°C was delayed

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5 days by sealing in polyethylene bags (0.02 mm thickness) with C_2H_4 absorbent without any abnormal flavour.

'Tommy Atkins' and 'Keitt' mangoes were individually sealed in shrinkable Cryovac polyolefin films (15 or 19 mm thickness), either non-perforated (MD film) or perforated with 8 holes of 1.7 mm diameter per inch^2 (MPY) or 8 holes of 0.4 mm diameter per inch^2 (SM60M) (Rodov *et al.*, 1994). After 2–3 weeks at 14°C and an additional week at 17°C, mangoes packaged in perforated polyolefin films ripened normally with optimum results achieved when film with 0.4 mm perforations was combined with increased free volume inside the package by sealing the fruit within polystyrene trays. After 3 weeks of storage and 1 week of shelf life, sealed 'Keitt' mangoes were inferior to the control; they were less ripe, but beyond 4 weeks (up to 6 weeks) sealed fruit had better quality scores because they were less overripe. Sealing did not reduce decay of fruit stored for long periods.

Non-perforated PVC film packaging of 'Nam Dork Mai' mangoes was not sufficiently permeable for O_2 exchange to allow proper ripening (Yantarasri *et al.*, 1995). Therefore, a so-called 'perforated MA' was used in which fruit were wrapped in polystyrene trays (three fruit per pack) at 20°C with perforation area of $\geq$0.004 cm^2. Fruit ripened normally with no off-flavours. Colour development in the peel required a higher concentration of O_2 than the flesh. A film of pore area $\geq$0.008 cm^2 allowed fruit colour to develop after 3 weeks while a pore area of $\geq$ 0.39 cm^2 allowed the fruit to colour within 2 weeks.

Some fruit coatings can create an internal MA within the fruit due to semipermeable restriction of O_2 and CO_2 movement in and out of the fruit. Baldwin *et al.* (1999) tested two types of fruit coatings – polysaccharide-based and carnauba wax-based – for their effect on external and internal mango fruit atmospheres and quality factors during simulated commercial storage at 10 or 15°C with 90–99% RH followed by simulated marketing conditions at 20°C and 56% RH. The coatings exhibited markedly different O_2 permeability characteristics under laboratory conditions. Polysaccharide coatings were less permeable to respiratory gases (i.e., O_2 and CO_2) and more permeable to water vapour compared to carnauba wax. When applied to fruit under simulated commercial conditions, however, the differences between the coatings in permeance to respiratory gases were much reduced, most likely due to the high RH during cold storage. Both coatings created a MA within the fruit, reduced decay, and improved appearance by imparting a subtle shine; but only the polysaccharide coating delayed ripening and increased concentrations of flavour volatiles. The carnauba wax coating significantly reduced water loss compared to uncoated and polysaccharide-coating treatments. 'Julie' mangos treated with 0.75% w/v aqueous solution of 'Pro-long' semipermeable fruit coating (a mixture of sucrose esters of fatty acids and sodium salt of carboxy methyl cellulose) and stored at 25°C and 85–95% RH exhibited reduced weight loss, retarded ripening, and increased storage life (6 days longer) without evidence of any adverse effects on quality (Dhalla and Hanson, 1988). A treatment with 1.0% 'Pro-long' could increase ethanol concentration in the

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pulp. Treatment with 'Pro-long' (0.8–2.4%) also delayed ripening of 'Haden' (Carrillo-Lopez *et al.*, 1996).

22.6 Physiological disorders

Mango fruit are susceptible to various physiological disorders that are either induced or inherent, and several of them become apparent during fruit ripening (Yahia, 2005). Some disorders, such as chilling injury (CI) and heat injury, may be induced after harvest, while others are inherent. Examples of inherent physiological disorders include the 'spongy stem-end' in 'Kensington Pride' (Brown *et al.*, 1981), 'soft nose' in Florida mangoes (Young, 1957), 'internal breakdown', 'spongy tissue' or 'soft nose' in Indian 'Alphonso' mangoes (Subramanyam *et al.*, 1971).

22.6.1 Biennial bearing

Biennial or alternate bearing is a major problem in several mango growing regions, especially in Asia and Africa. This disorder, which results in significant reduction in yield, is less of a problem in regions where humidity is relatively high with lower temperatures. This problem has been attributed to several factors such as genetic, physiological, environment, and nutritional. However, the problem is augmented by the poor handling of the tree, especially the lack of adequate pruning, and inappropriate fertilizer programmes.

22.6.2 Internal breakdown (jelly seed, soft nose, stem-end cavity, spongy tissue)

This is characterized by a breakdown in the flesh on the ventral side and toward the apex of the fruit (Yahia, 2005; Yahia *et al.*, 2006a). In 'Haden' mango, there is a yellowing of the green skin at the apex, which becomes soft. The tissue becomes spongy and greyish black at the advanced stage of the disorder. Amin (1967) described 'spongy tissue' as white sponge-like corky tissue, slightly desiccated in nature, in the pulp between the skin and the stone of the ripe fruit. In rare cases, when injury can be seen from outside, the skin turns brownish-black forming a flat external depression. Commonly, the pulp remains unripe because of the unhydrolysed starch (Katrodia, 1979). In some cases mechanically injured fruits develop spongy-like symptoms, where the exocarp may or may not be injured. These symptoms can be differentiated from the natural spongy tissue symptoms by the papery-white dead tissue developed in the pulp and on the stones and the absence of any browning reaction around the damaged tissue (Katrodia, 1989). The cause of this disorder is not completely known. In 'Alphonso' mango, the internal breakdown symptom is revealed when the fruit is cut open (Subramanyam *et al.*, 1971). The tissue becomes soft or spongy, with or without off-flavour, and the disorder commences from the stone and spreads toward the periphery. In

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severe cases, the whole fleshy tissue becomes too soft, resembling bacterial rot. X-ray photographs and x-ray images of fruits having spongy tissue show dark grey patches corresponding to internal cavities, in contrast to light grey areas of healthy tissue (Thomas *et al.*, 1993).

These disorders are cultivar dependent (Burdon *et al.*, 1991). For example, in the Canary Islands 'Kent' and 'Ameeri' were reported to be very susceptible to soft-nose, and harvesting at the green-ripe stage reduced the incidence of the disorder (Galan Sauco *et al.*, 1984). Spongy-tissue affected pulp was reported to have higher acidity, lower pH, low ß-carotene content, low sugars and ascorbic acid content, and high starch content with lower amylase and invertase activities (Katrodia, 1989). Low calcium in the fruit from the site prone to soft-nose was suggested as a possible contribution factor to the initiation of this disorder (Burdon *et al.*, 1991). Calcium and magnesium content in the disordered 'Kent' fruit was lower than the content in the healthy fruit of the same cultivar. However, levels in the less susceptible 'Beverly' fruit were as low as the disordered 'Kent' fruit at the same site. The inner flesh of the distal region of the fruit, the location at which the soft-nose disorder develops, was found to have the lowest calcium concentration in the whole fruit (Burden *et al.*, 1991). Heat arising by convection from the soil was suggested as the main cause of damage to mature 'Alphonso' on the tree (Katrodia and Rane, 1979). This convective heat was suggested by these authors to cause more injury in the lower part (apex) than in the lower or middle parts of the fruit. It has also been suggested that covering of the soil by natural vegetation (sodculture) in the orchard prevents the occurrence of spongy tissue in the fruit while on the tree. The earlier harvesting of the fruit and its subsequent ripening with ethylene was reported to reduce the incidence of spongy tissue disorder in 'Alphonso' mangoes (Lad *et al.*, 1985).

22.6.3 Chilling injury (CI)

Mango fruit is sensitive to low temperatures if the storage duration exceeds one day at near 0°C to a few weeks at just below 12°C (Yahia, 2005). This problem limits the use of low temperature during storage and shipping, and thus reduces potential postharvest life. CI symptoms often are not apparent during storage but develop later, when the fruit are brought to warmer temperatures. The symptoms of CI include greyish, scald-like discolouration on the skin, followed by pitting, uneven ripening, and poor flavour, aroma and colour development (Medlicott *et al.*, 1990; Yahia, 2005). Other symptoms in mango fruit injured by chilling include discoloured and pitted areas on the surface (Kane, 1977) followed by increased susceptibility to microbial spoilage (Sadasivam *et al.*, 1971; Subramanyam *et al.*, 1975). Chilling susceptibility varies with cultivar (Farooqui *et al.*, 1985; Yahia, 2005); 'Haden' and 'Keitt' mangoes are particularly susceptible, and 'Sensation' mangoes developed more skin symptoms than 'Sammar Bahisht' mangoes. CI can be reversed if the time of holding at low temperature is not as long. Variation exists in the degree of sensitivity of the different cultivars to CI.

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While CI has generally been reported to occur in mango fruit at temperatures below about 10–13°C, some cultivars ('Dasheri', 'Langara') were reported to be safely stored at 7–8°C for up to 25 days (Mann and Singh, 1976). While most cultivars show injury below 10°C if fruit have just reached maturity, tolerance to CI increases as fruit ripen (Mohammed and Brecht, 2002).

The best control of CI is to avoid exposure to temperatures lower than optimum. Optimum minimum temperature for mango depends on the cultivar and ripening stage. Other measures include maintenance in modified/controlled atmospheres, and conditioning at high temperatures (35–38°C) for a few hours before storage at low temperature. Tolerance of 'Keitt' mango fruit to CI was induced by pre-storage heat treatments (McCollum *et al.*, 1993). Mango tolerance to CI was reported to increase after pre-storage heat treatments (McCollum *et al.*, 1993). CI symptoms in 'Keitt' mangoes kept at 38°C for 0, 24 or 48 h before storage at 5°C for 11 days decreased with increased duration at 38°C, while non-heated fruit developed severe CI symptoms (McCollum *et al.*, 1993).

22.6.4 Other physiological disorders

Mango is considered to be among the fruits more tolerant to heat (Yahia *et al.*, 2000; Jacobi *et al.*, 2001b), but heat may cause injury, especially if the fruit are exposed to temperatures higher than 30°C for more than 10 days, although injury can also occur in shorter periods at higher temperatures. The heat disinfestation treatments applied for insect quarantine security and decay control may injure fruit that are not fully mature (Yahia and Campos, 2000; Jacobi *et al.*, 2001a). External symptoms of heat injury include lenticel spotting and skin browning ('scald') with secondary disease development, while internal symptoms include mesocarp browning, tissue cavitation and 'starch spots'; in addition, ripening may be inhibited (Jacobi *et al.*, 2001a;b; Yahia and Campos, 2000).

The 'black tip' disorder is characterized by yellowing of tissues at the distal end of the fruit, and the colour intensifies into brown and finally black, the mesocarp and seed being unaffected (Yahia *et al.*, 2006a). This is usually followed by the appearance of grey spots of indefinite outline in the etiolated tissue, which turn brown and coalesce, and the entire fruit tip turns brownish-black (Ram, 1989). This disorder was reported to be caused by the emanation of gases from brick kiln fumes, such as sulphur dioxide, ethylene and carbon monoxide. A spray of 1% borax at the time of fruit set, followed by two more sprays at 10-day intervals, or a spray of washing soda (0.5%) and caustic soda (0.8%) can be useful in controlling the disorder (Yahia *et al.*, 2006a).

A 10 kPa CO_2 atmosphere alleviated CI symptoms in fruit of 'Kensington Pride', but higher concentrations are injurious and low O_2 (5 kPa) has no significant effect (O'Hare and Prasad, 1993). Higher concentrations of CO_2 (>10 kPa) are ineffective for alleviating CI at 7°C, and tend to cause tissue injury and high levels of ethanol in the pulp. Injury in 'Kensington Pride' caused by higher levels of CO_2 appears to be more severe at lower temperatures (O'Hare and

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Prasad, 1993; Bender *et al.*, 1994; 1995), which could be due to either compounding injury (chilling + CO_2) or reduced sensitivity of ripe mango to CO_2. 'Rad' mangoes develop internal browning and off-flavour in atmospheres containing 6 and 8 kPa CO_2 (Noomhorm and Tiasuwan, 1995). The presence of starchy mesocarp in 'Carabao' mangoes, which is characteristic of internal breakdown, increases during storage in MA (Gautam and Lizada, 1984).

Fruit stored for 4–5 days have severe symptoms, including air pockets in the mesocarp resulting in spongy tissue (Nuevo *et al.* 1984a;b). External symptoms of internal browning due to MA include failure of the peel to develop colour beyond the half-yellow stage. 'Carabao' mangoes stored in polyethylene bags (0.04 mm thickness) had a faint fermented odour that disappeared during ripening when the fruit were held for 1 day (Gautam and Lizada, 1984). The fermented odour increases with time, and persists throughout ripening when the fruit is stored for 2 to 5 days. The respiratory quotient of this cultivar ranged from 0.59 at 21 kPa O_2 to 6.03 at 2.4 kPa O_2, which indicates a progressively anaerobic metabolism (Sy and Mendoza, 1984). The CO_2 production decreases as O_2 decreases from 21 to 3 kPa, but increases below 3 kPa O_2. Pronounced decay appears after storage of 'Rad' mangoes for 20 days in atmospheres containing 4–6 kPa O_2 plus 4–8 kPa CO_2 at 13°C and 94% RH, and severe incidence appears after 25 days (Noomhorm and Tiasuwan, 1995). Greater incidence of decay (stem-end rot and anthracnose) occurs in 'Carabao' mango stored in MA for 2 to 5 days at 25 to 31°C (Gautam and Lizada, 1984).

22.7 Pathological disorders and their control

22.7.1 Diseases

Decay is one of the most important causes of postharvest losses in mango. The major postharvest diseases of mango fruit (anthracnose, alternaria spot, stem-end rot) result from infections that occur on the tree or during harvest, but usually do not become visible until the fruit ripens. Anthracnose and alternaria spot develop from quiescent lesions on the peel; stem-end rots infect injuries and can occur due to fruit contact with soil during harvest. Disease control in mangoes needs to be primarily managed by preharvest practices. Postharvest chemical treatments are available but may not be feasible due to the receiving country regulations regarding chemical residues. In some countries, mangoes are dipped in 49–55°C water for 3 to 15 min, which is an effective treatment for anthracnose. The hot water treatment required for fruit fly control in mangoes (46.1°C for 65 to 110 min, depending on fruit weight) has also been shown to reduce anthracnose and stem-end rot.

Anthracnose

Anthracnose is the most serious disease in most mango-growing regions, especially those with high rainfall and humidity. This disease is caused by *Colletotrichum gloeosporioides* (Penz) Sacc., *Glomerella cingulata* (Stonem).

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Spauld and V. Schrenk conidial state, and to a lesser extent *Colletotrichum acutatum* Simmonds (Simmonds, 1965; Yahia, 2005). Infection can be on the fruit, but also on blossoms, leaves, twigs and young branches (Jeffries *et al.*, 1990; Dhua and Roychaudhuri, 1996). Infection of fruit by *C. gloeosporioides* occurs prior to harvest from waterborne conidia spread from dead twigs and leaves (Johnson and Coates, 1993). In addition to attack through the wounds, the organism could penetrate the fruit through the cuticle and natural openings on the fruit surface. In the fruit, the infection is latent and starts to develop as the fruit advances in its stage of ripening. *C. gloeosporioides* causes large, spreading lesions on the surface of the fruit (Muirhead and Grattidge, 1984) that take the form of dark sunken patches up to 20 mm wide, at any point on the fruit surface (Lonsdale, 1992).

Stem-end rot

Stem-end rot is second to anthracnose in importance in many mango-growing regions. It has been shown to be caused by *Lasioidplodia theobromae* (Pat.) Griff and Maubl (syn. *Botryodiplodia theobromae* Pat.) alone (Lim and Khoo, 1985; Prakash and Srivastava, 1987). However, *L. theobromae, Phomopsis mangiferae* Ahmad and *Dotiorella dominicana* (Sacc.) Petr. and Syd. were reported to cause stem-end rot in Australia, Thailand and Malaysia (Sepiah, 1986; Sangchote, 1987). The disease usually starts at the stem end of the fruit but the fungi can attack any part of the fruit, especially parts injured during harvesting or handling. Endophytic colonization of the inflorescence and pedicel tissue was found to be the primary route of infection of fruit that develop stem-end rot during ripening (Johnson *et al.*, 1992). Storage at 30°C favoured infection by *L. theobromae* over that of *D. dominicanaas*, and the reverse occurred at 25°C and lower, which explains the possible different causes of the disease in tropical and in sub-tropical growing areas (Johnson *et al.*, 1992). Infection can be reduced by leaving a pedicel of about 1–2 cm on the fruit.

Alternaria rot

Alternaria rot, which is caused by *Alternaria alternata*, can cause serious losses when anthracnose and stem-end rot are absent or well controlled, but it is only a problem during storage of mango for 3 weeks or more (Johnson and Coates, 1993; Yahia, 2005). *A. alternata* infects mangoes through the lenticels and penetrates the fruit, resulting in darkening of the intercellular spaces and cell collapse (Prusky *et al.*, 1983). The symptoms of this disease consist of either small black spots (0.5–1.0 mm in diameter) with dark centre and diffusive borders, or dark lenticels. At least 350 h of RH over 80% were reported to be needed for a significant incidence of quiescent infections of *A. alternata* to establish during development (Prusky and Gat, 1992). After infection in the orchard, the hyphae remain latent until the fruit ripens, and then develop intercellularly. The quiescent periods in mangoes inoculated with *Alternaria tenuis* Nees, *C. gloeosporioides* and *L. theobromae* were 14, 3 and 4 days, respectively, indicating that alternaria rot appeared later than anthracnose.

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Aspergillus rot
Black mould, which is caused by *Aspergillus niger* and other *Aspergillus* spp., can be a serious postharvest disease in mango fruit exposed to high temperatures and rough handling (Prakash and Srivastava, 1987; Muirhead and Grattidge, 1984; Yahia, 2005). The affected fruit show yellowing at the base, and develop irregular, greyish spots which coalesce into dark brown or black lesions, and the mesocarp becomes depressed and soft.

Other diseases
Other diseases that can attack mango fruit after harvest include Rhizopus (caused by *Rizopus oryzae*), scab and sooty mould (caused by *Cannodium mangifera*) (Yahia, 2005). *Rhizopus* is usually a result of mechanical injury. *Botryodiplodia theobromae* can proliferate on green, unripe as well as ripe fruit and can cause total spoilage of the fruit within 48 h, but needs mechanical injury for infection (Yahia *et al.*, 2006a).

22.7.2 Control

Decay control is accomplished with an adequate preharvest and postharvest integrated programme (Yahia, 2005). In postharvest, washing water usually contains about 100 ppm of sodium hypochlorite, and may contain fungicides depending on the extent of the problem. Careful handling of the fruit, elimination of mechanical injury, rapid cooling, and maintenance of low (optimum) temperature, and maintenance of hygienic conditions are essential for decay control (Yahia, 2005).

Biological control
Antifungal resorcinols, present in the peel of mango fruit, interfere with the development of anthracnose and *Alternaria* rot (Cojocaru *et al.*, 1985; Droby *et al.*, 1986; 1987), with higher levels present in some cultivars (Droby *et al.*, 1986). Bacteria active against mango isolates of *C. Gloeosporioides*, stem-end and soft brown rot pathogens have been evaluated (Koomen *et al.*, 1990; Korsten *et al.*, 1991; 1992; 1993; Coates *et al.*, 1995). *Bacillus licheniformis* (Weigmann) Chester was found to be more effective in reducing fruit diseases than chemical treatments (Koresten *et al.*, 1991). Postharvest dip application in *Bacillus licheniformis* (isolates B250 and B251) effectively controlled anthracnose and stem-end rot, and B251 effectively controlled soft brown rot (Korsten *et al.*, 1992).

Chemical treatments
Fungicides are sometimes needed, especially when hot water treatment is not used (Yahia, 2005). However, when combined with hot water the effectiveness of penetration and action of the fungicide increase. If fungicides are applied in water at high temperature, the concentration of the fungicide can be reduced. When fungicides and or wax are applied as spray, one should consider the number, type

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and distribution of the nozzles, and the time for which the fruit is exposed to the treatment. When treatment is done as dipping, the tank should be made of a material that does not react with any of the chemical material, and should be resistant to corrosion and easily cleaned. These tanks are usually made of fibreglass, plastic, stainless steel or steel with a protective cover. Use of imazalil in hot water has been reported to result in complete control of anthracnose and stem-end rot in several mango cultivars (Yahia *et al.*, 2006a). Prochloraz (250–800 ppm for 15–20 seconds) also provides good control of anthracnose and *Alternaria* rot, but not adequate control of stem-end rot. FAO recommends a maximum residue level of 2 mg kg^{-1} prochloraz in mango fruit (Yahia *et al.*, 2006a). Although the maximum residue levels are estimated for the whole fruit, most of it is usually found in the skin. For example, residues in 'Kensington' mango were found 7 days after treatment to be 17 mg kg^{-1} in the skin, in whole mangoes to be 1.7 mg kg^{-1}, and in the flesh to be less than 0.1 mg kg^{-1}.

Heat treatments

Heat is used to treat mangoes for both disease control and insect disinfestation (see below), and care must be exercised to avoid exceeding the time–temperature limitations of those treatments in order to avoid fruit injury (Yahia, 2005). Hot water treatment for insect disinfestation can control some pathogens. However, fruit that do not have to be treated with the long hot water treatments for insect control can be exposed to hot water (with or without fungicides) for short periods for the control of decay. These treatments consist of temperatures of 48–55°C for 3 to 15 min, depending on cultivar and the extent of the problem (Yahia, 2005). 'Haden' and 'Tommy Atkins' mangoes are treated for about 3 minutes. Treatment is applied immediately after receiving and washing of the fruit in the packhouse. Right after hot water treatment, fruit should be cooled in ambient or cold water. Hot water is more effective for the control of anthracnose than for stem-end rot. Shorter treatments are sufficient for anthracnose (about 3 minutes), while stem-end rot usually needs longer treatments (7 minutes or more). Hot water tanks are of different sizes. They should be built from material that will not corrode rapidly (stainless steel and fibreglass are commonly used). Tanks should be equipped with temperature devices, and water should circulate to result in a uniform temperature. Tanks should be equipped with filters to avoid accumulation of soil, debris, etc.

Heat treatments are highly preferable for the following reasons: they are non-chemical treatments, they can delay ripening and senescence when used adequately (and thus delay development of diseases), and they can increase resistance of the fruit to CI. In addition, hot air is compatible with the use of MA/CA for disease and insect control.

Irradiation

Irradiation was tested for disease control in mango. A dose of 1000 Gy was suggested for the control of anthracnose (Tandon and Singh, 1968; Jacobs *et al.*, 1973). Severity of anthracnose caused by *Colletotrichum gloeosporioides* Penz. was reduced in 'Keitt' mangoes exposed to 500 Gy or higher, and the

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severity of stem-end rot caused by *Diplodia natalensis* P. Evans or *Phomopsis citri* Fawe. was reduced in 'Tommy Atkins' mangoes exposed to 1500 Gy, but not to 750 Gy (Spalding and von Windeguth, 1988). These authors reported that the overall percentage of decayed fruit was reduced by irradiation at 750 Gy or higher. However, these high irradiation doses are known to cause injury to most mango cultivars (Yahia, 2005). Doses of 750 Gy caused 15% peel injury in 'Tommy Atkins' and 29% in 'Keitt' mangoes (Burditt *et al.*, 1981).

Ultraviolet C (UV-C) radiation treatment of 'Tommy Atkins' mangoes for 10 min was reported to be effective in suppressing decay, and increasing the levels of putrescine and spermidine (Gonzalez-Aguilar *et al.*, 2001). One-minute exposure to short-wave infrared radiation followed by a 20-s prochloraz dip (81 g a.i/100 l) was reported to effectively control anthracnose and soft brown rot (Landsdale and Droomer, 1994).

22.8 Insect pests and their control

22.8.1 Insect pests

Mango pests include internal pulp feeders such as fruit fly immatures, seed pests such as mango weevil, and external pests such as scales, mealybugs, thrips, and mites (Yahia, 2005). Of the 260 species of insects and mites reported to have been recorded as minor and major pests of mango, 87 are fruit feeders (Peña and Mohyuddin, 1997). Key pests, which include fruit flies, seed weevils, tree borers and mango hoppers require annual control measures. Secondary pests generally occur at subeconomic levels, but can become serious pests as a result of changes in cultural practices and mango cultivars or because of indiscriminate use of insecticides against a particular pest (Peña and Mohyuddin, 1997). For example, scale insects were reported to become serious pests following non-judicious use of insecticides against fruit flies. Only fruit flies, seed weevils and lepidopterous larvae actually fully penetrate the fruit pulp and seed. Other pests such as *Othreis materna* (L.), *Gonodonta pyrgo* (Cram.), *G. clotilda* (Stoll) and *Leptoglossus stigmatai* (Herbest) often extend only a short distance into the pulp of ripening mangoes (Peña and Mohyuddin, 1997). External pests pose a risk because they may be present on the fruit surface as hitchhikers, but they can be detected visually by inspectors and must be removed before the fruits are shipped. Immature mango seed weevils (*Cryptohynchus mangiferae* F.) occur in mango seed, but not in the flesh, and are difficult to control without damaging the market quality of the treated fruit. A related weevil (*Sternochetus gravis* F., sy. *S. frigidus* F.) occurs in rainfall regions in India and Southeast Asia, and causes severe damage to the fruit pulp (Cunningham, 1986).

Fruit flies

The most economically important mango pests are fruit flies of the family Tephritidae (Yahia, 2005). They are considered the most important insect pest risk carried by exported fruits worldwide. Forty-eight species of fruit flies have been

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reported to attack mango as well as related species (*M. foetida*), including eight species of the genera *Anastrepha*, 30 species of the genera *Bactrocera*, seven species of the genera *Ceratitis*, two species of the genera *Dirioxa* and one species of the genera *Toxotrypana* (Yahia *et al.*, 2006a). Eggs of fruit flies are deposited under the peel and larvae feed and tunnel through the pulp tissue.

Seven *Ceratitis* spp. have beeen reported to attack mango fruits (Peña and Mohyuddin, 1997). The Mediterranean fruit fly (*Ceratitis capitata* Wiedemann) is a common polyphagous pest, established in 95 countries, and considered the most destructive among the many fruit flies. Other species of this insect such as *C. rosa* and *C. cosyra* are known to attack mango in Africa (Yahia *et al.*, 2006a).

Anastrepha spp. are endemic to the western hemisphere, extending from the southern US to northern Argentina including the Caribbean islands (Aluja, 1994). Eight *Anstrepha* species have been reported to attack mango (Yahia *et al.*, 2006a). The West Indian fruit fly (*A. obliqua*) has been reported to be the most common fruit fly pest when compared with other neotropical species (Yahia *et al.*, 2006a). In the majority of *Anastrepha* species, the females deposit their eggs (15–19 eggs per *A. ludens* female) in either the epicarp or mesocarp of ripening fruit, either singly or in clusters depending on the species. Larvae pass through three instars before emerging from the fruit and burrowing into the ground to pupate. Egg incubation of *A. ludens* in mango was reported to require 3.8 days, larval development requires 14.2 days and pupal development requires 14.2 days at 27°C. Cultivars vary in their resistance to *Anastrepha* spp. (Yahia *et al.*, 2006a). Mango fruit contains resin ducts located in the exocarp which confer protection against two types of movement in the exocarp: the vertical movement of the ovipositor and larval movement (Joel, 1980).

Bactrocera spp. are pests of major importance in the eastern hemisphere. The common species reported on mango include the Queensland fruit fly (*B. tryoni* Frogatt), Oriental fruit fly (*B. dorsalis* Hendel), *B. zonata* (Saunders), *B. neobumeralis* (Hardy), *B. jarvisi* (Tryon), and *B. frauenfeldi* (Schiner) (Yahia *et al.*, 2006a). The oriental fruit fly (*B. dorsalis*) is one of the most serious pests in some countries (such as India).

Monitoring of fruit flies is extremely important. Dropped fruits in the orchard must be collected and destroyed weekly since the larvae of fruit flies emerge from these fruits and pupate in the soil. Pre-harvest control is normally done by weekly application of a toxic bait consisting of a mixture of insecticide plus an attractant and water. The bait treatments commonly used for mango are mercaptothion plus protein hydrolysate, or trichlorfon and protein hydrolysate. The toxic bait is applied to a portion on only one side of the tree in the form of large droplets at a rate of about 250–1000 ml per tree, depending on tree size (Joubert *et al.*, 2000).

A maximum pest limit approach was used to determine the probability of pest introduction into the US when commodities are hosts to the Mexican fruit fly (*A. ludens*) (Yahia *et al.*, 2006a). Ecological parameters including the proportion of fruit infested and the number of pests per infested fruit were assessed under various pest management scenarios for mangoes and citrus in regions of Mexico

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that are infested with the fly. This study indicated that standard preharvest pest management practices such as insecticide application, sterile insect release or the selective harvest of fruit reduced the predicted survival rate in treated fruit to levels below two fruit flies per shipment. However, if no pest management was carried out, infestation levels in fruit frequently resulted in survival levels exceeding the maximum pest level following a postharvest treatment that had been shown to be at least 99.9968% (probit 9) effective. Therefore, it has been concluded that a postharvest quarantine treatment with demonstrated efficacy corresponding to at least 99.9986% mortality is only effective in maintaining a predicted pest survival of less than one reproductive pair of flies per shipment when combined with current preharvest pest management practices.

Mango weevils

Mango is the only known host for the mango weevil (*Cryptorhynchus mangiferae* F.), which is found throughout all the mango-growing regions, except in North and South America, and the Caribbean (Shukla and Tandon, 1985), and therefore it is a quarantine pest. The weevil is primarily a pest of the seed, with one seed supporting up to five larvae, although occasionally it may be found in the fruit flesh. Eggs are laid on the outside of the developing fruit and the enclosing larvae penetrate the young seed, where the weevil completes its development. Mango weevil oviposition occurs when the fruit is marble size, and may occur in less than 8 days or up to 90 days (Shukla and Tandon, 1985). As the fruit matures and the seed covering becomes hard the first instars will not be able to penetrate the endocarp. Fruits fallen on the ground can become sufficiently damaged to allow the weevils to move out of the seed and seek hiding places where they over-season (Yahia *et al.*, 2006a).

Mango seed weevil is an important limiting factor for the international trade of mango and prevents the export of fresh fruit into areas uninfested with this pest (Hansen, 1993). The flesh of ripe fruit is damaged when adults emerge from the seeds, and weevil-damaged seeds may limit plant propagation in nurseries and orchards (Johnson, 1989). Premature fruit drop may be caused by severe weevil infestation.

X-ray imaging was reported to have potential for detecting seed weevil infestation in mango fruit (Reyes *et al.*, 2000). X-ray film image of weevil-infested mango fruit has a distinct feature of dark grey patches corresponding to the cavities within the seed, proving positive detection of weevil infestation.

22.8.2 Insect quarantine treatments

Integrated pest management strategies adequately control orchard pests while reducing reliance on pesticides (Yahia, 2005). Measures to control insects include preharvest and postharvest programmes. Preharvest programmes include cultural practices, traps, chemical treatments and use of sterilized insects. Preharvest chemical control has been achieved using organophosphates and hydrolysed albumen. This is usually based on baited traps and the appearance of the first

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trapped males. The chemical control agents are dimethoate (0.1%) and fention (15%). Weekly application of malathion is commonly used. For example, adult fruit flies can be controlled by bait sprays of carbaryl (0.2%) + protein hydrolysate (0.1%) or molasses starting at preoviposition stage (2 weeks after fruit set), repeated after 21 days. The use of hang traps (about ten traps for each hectare of orchard) containing 100 mL emulsion of methyl euginol (0.1%) and malathion (1%) during fruit development is another control method used. The use of poison bait containing mercaptothion, trichlorfotm or protein hydrolyzate has been practised against fruit flies. Removal of fallen fruits is important to prevent build-up of insect populations. Postharvest treatments include the use of chemicals, high temperatures and irradiation.

Chemical control

Chemical control of the Mediterranean fruit fly has been achieved by applying organophosphates and hydrolysed albumen. Chemical application is based on monitoring by Trimedlure-baited traps, and the appearance of the first trapped males. The chemical control agents are dimethoate (1%) and fenthion (0.15%). The bait spray is based on Neziman (1:1 protein hydrolysate:malathion in 4:1 of water) (Yahia *et al.*, 2006a). *Anastrepha* flies are susceptible to most insecticides.

Fumigation with ethylene dibromide (EDB) has been a traditional treatment for fruit fly disinfestations, but this treatment is no longer registered for use. The ban on EDB resulted in methyl bromide (MeBr) becoming the treatment of choice for achieving quarantine security for fresh horticultural crops in several countries. However, in 1992, MeBr was determined to be an ozone depleter and subsequently the US EPA included it as a chemical to be removed from use by 2001 (Clean Air Act, 1991, Title VI, section 602). In October 1998, the US Congress, under the 1999 Appropriations Bill altered the US Clean Air Act (Sec. 764.a) to reflect the restrictions of the Montreal Protocol. This meant that restrictions on the use of MeBr would be exempt for postharvest and phytosanitary uses. Postharvest dipping in dimethoate has been reported to be effective against Queensland fruit fly in 'Kensington' mangoes, and has been used for fruit entering Australian states except Queensland and New South Wales (Swaine *et al.*, 1984).

Heat treatments

Heat treatments have been reported to delay ripening, control insects and diseases, and to ameliorate CI in several horticultural crops (Yahia *et al.*, 2006a).

Hot water immersion is an efficient treatment for mango disinfestation of fruit flies. The use of hot water immersion has intensified after the Environmental Protection Agency (EPA) initiated actions in 1986 to eliminate the use of EDB due to health concerns. Animal and Plant Health Inspection Service (APHIS, 1987) approved a hot water immersion quarantine treatment that destroys immature tephritidae in mangoes. Currently, hot water treatments are used in several countries as quarantine treatments for mango and papaya fruits (Fig. 22.3). For example, mangoes are treated with hot water immersion at a temperature of 46.1 to 46.5°C for 65 to 110 min, depending on fruit weight. Probit analysis estimated that the

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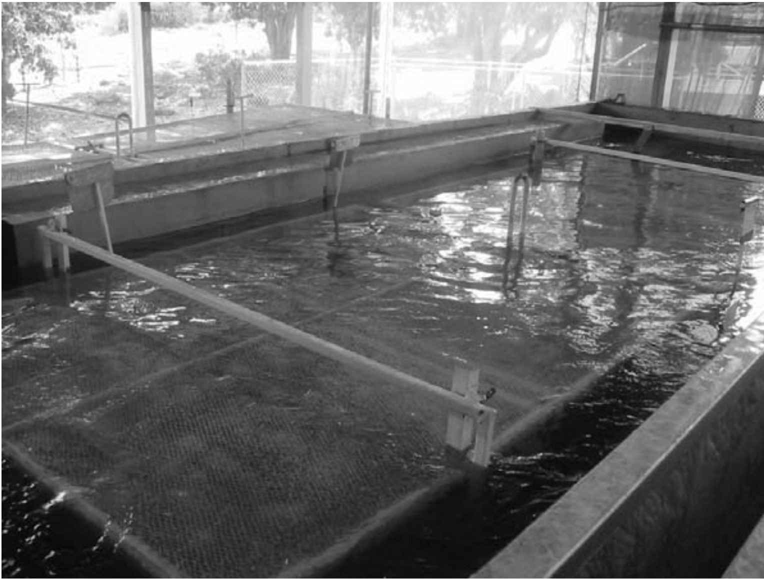

Fig. 22.3 Hot water tank.

immersion time needed to reach Probit 9 security for laboratory strain of *A. ludens* at 46.1°C was 65.1 min, and for a wild strain was 72.4 min (Sharp *et al.*, 1989a). For *A. obliqua* immersion time needed was estimated as 66.8 min for laboratory strain and 83.6 min for a wild strain (Sharp *et al.*, 1998a).

In a large scale test of artificially infested mangoes of different cultivars, immersion in water at 46.1°C for 90 min resulted in no pupal survivors of wild strains of either spp. (Sharp *et al.*, 1989a). Larvae and eggs of Caribbean and West Indian fruit flies are killed when infested mangoes are immersed for 1 hr in water at 46.1°C. 'Tommy Atkins' and 'Keitt' mangoes infested with immature stages of *A. suspensa* showed that immersion in water at 46°C for 65 min killed eggs and 1–2-day-old larvae and prevented adult emergence from the pupae that developed (Sharp, 1986), without noting any damage in fruit quality. Probit 9 security was reached in 67.5 min for *C. capitata* and 64.5 min for *A. serpentina* when artificially infested mangoes were immersed for 20–80 min in water at 45.9–47.1°C (Sharp *et al.*, 1989b). Large scale tests with artificially infested fruits confirmed that there were no survivors following fruit immersion in water at 45.9–47.1°C for 90 min (Sharp *et al.*, 1989b). Estimated immersion times needed to reach Probit 9 mortality after artificially infested 3rd instar larvae in 'Haden' and 'Kent' mangoes were 76.1 min for *C. capitata*, 113.4 min for *A. obliqua*, 65.8 min for *A. distincta* and 75.6 min for *A. fraterculus* (Sharp and Picho-Martinez, 1999). The 99% lethal time dose for third-instar larvae of *A. ludens* exposed to 44°C core temperatures in artificial fruit was 61.5 min when a slow heating rate (120 min ramp) was applied, and only 41.9 min when a fast heating rate (15 min ramp) was applied. The immersion of five Australian cultivars

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in water at 48°C for 30 min was reported to kill eggs and larvae of *B. aquilonis*, however 'Kensington' mango is more sensitive to hot water than to vapour heat (Jacobi *et al.*, 1994). Hot water treatment immersion is not effective as a quarantine treatment to disinfect mangoes of the mango weevil. Weevils in 'Alphonso' mangoes from India were not killed when infested mango fruit were immersed in water at 48–52°C for up to 90 min, and 54–70°C for up to 5 min (Shukla and Tandon, 1985). Currently there are approximately 75 commercial hot water treatment facilities in Mexico, 5 in Ecuador, 6 in Guatemala, 11 in Peru and 10 in Brazil.

Hot water immersion, especially when applied inadequately or when fruit is not cooled after treatment, can damage the quality of mango fruit (Yahia and Campos, 2000). Small fruit are commonly damaged more readily by heat than large fruit, and grading before heat treatments is therefore required. Some of the factors to reduce fruit injury by heat include delaying treatment for 24 hrs after harvest, and treatment of more mature fruit (Jacobi *et al.*, 1994). Spalding *et al.* (1988) reported that immersion in hot water (46 °C for 60–90 min, followed by storage for 3 days at 13 °C and ripening at 24 °C) did not damage the market quality (ripening time, pH, total titratable acidity, ascorbic acid, soluble solids content) of 'Tommy Atkins' and 'Keitt' mangoes. However, lenticels were darker on 'Tommy Atkins' fruits immersed in water at 46 °C for 120 min, on 'Keitt' mangoes immersed in water for 90 min at 46 °C, and on both cultivars immersed for 60 min at 49 °C. Anthracnose was reduced in 'Keitt', and stem-end rot was reduced on both cultivars immersed in water at 46 °C or 49 °C. Immersion of 'Oro' mangoes for 75 min at 46.1°C caused no damage, while 80%, 85% and 15% of the fruit were acceptable after immersion for 90, 105 and 120 min, respectively (Sharp *et al.*, 1998a). 'Tommy Atkins' and 'Keitt' mangoes immersed for 90 min and then refrigerated at 11.1°C for 7, 11 or 14 days were not damaged. 'Haden' mangoes immersed for 90 min and then held at 24 °C were acceptable for 12 days (Sharp *et al.*, 1989a). Most 'Ataulfo' mangoes (93.3%) immersed in water at 46.1°C for 90 min and cooled at 11.1°C for 14 days were acceptable, but when stored at 23–24 °C only 13.3% were acceptable after 7 days (Sharp *et al.*, 1998b).

Vapour heat treatments have also been used to disinfect mangoes of fruit flies (Yahia *et al.*, 2006a). Vapour heat raises the temperature of mangoes when air saturated with water vapour is heated between 40 and 50 °C. In this treatment heat is applied directly to the fruit surface by condensation of water vapour on the fruit. As early as 1935 Sein reported the control of all fruit flies in mangoes from Puerto Rico after exposure to vapour at 43 °C for 4 hrs. In 1937, vapour heat was used by Koidsumi to disinfect mangoes from Taiwan. In 1945, Balock and Starr reported that quarantine security (99.9968% mortality) was accomplished for *A. ludens* in mangoes from Mexico when exposed to vapour at 43.3°C for 13.7 hrs. Unahawatti *et al.* (1986) reported that vapour heat at 46.5°C disinfested mangoes of *Bactrocera dorsalis*. Melon fruit fly (*Bactrocera cucurbitae* Coquillett) immatures in mangoes from Okinawa were controlled with vapour heat at 44 °C and over 90% RH when the pulp centre reached 43 °C and remained there for 3 h (Sunagawa *et al.*, 1987). The vapour heat treatment for mangoes from Mexico is the same as that required for grapefruit, oranges and tangerines, while the vapour

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heat treatment required for mangoes from Taiwan consists of raising the fruit pulp temperature to 46.6 °C and maintaining it for 20 min (Yahia *et al.*, 2006a). Mango fruit from the Philippines and Thailand need to be treated with vapour heat at 46 °C (Philippines) and 46.5 °C (Thailand) and held at the respective temperature for 10 min (Japan Ministry of Agriculture, Forestry and Fisheries, 1992). New Zealand requires mango from Thailand to be vapour heat treated for fruit infestation by heating the fruit until seed surface temperature is 46.5 °C, and then held at that temperature for 10 min (Jacobi *et al.*, 2001). A vapour heat treatment schedule has been approved for use against the Queensland fruit fly (*B. tryonsi*) in 'Kensington' mangoes from Australia to Japan (Heather, 1994). In this treatment, the pulp temperature is raised to 46.5 °C and held at that temperature for 10 min (Heard *et al.*, 1992). A vapour heat treatment was also approved as a quarantine treatment for *A. ludens* and other *Anastrepha* species in 'Manila' and for mangoes from Taiwan infested with oriental fruit fly for import into the US.

Forced hot-air quarantine treatments were developed to disinfect mangoes of *A. suspensa* (Sharp, 1992) or *A. obliqua* (Mangan and Ingle, 1992). A mean centre pulp temperature of over 47 °C killed all stages of the West Indian fruit fly in Mexican-grown mangoes treated with hot air (Mangan and Ingle, 1992). A mean centre pulp temperature of over 46 °C killed all stages of the Caribbean fruit fly in Florida-grown mangoes treated with hot air (Sharp, 1992). These treatments consist of heating the fruit with 48.0 °C air for 160–220 minutes until the fruit seed surface temperature reaches 46.1°C or above to disinfect the fruit of Caribbean fruit fly (Sharp, 1992), or with 50 °C air for 133 or more minutes until the seed surface temperature is 48 °C to disinfect the fruit of West Indian fruit fly (Mangan and Ingle, 1992). The conditioned air is forced over the surface of the fruit and slowly heats the pulp. Condensation is not formed, and relative humidity is usually maintained at about 50%. 'Tommy Atkins' mangoes treated with forced air at 51–55 °C for 125 min and stored at 12 °C for up to 3 weeks before ripening at 21°C exhibited trace amounts of peel pitting with lower incidence of anthracnose and stem-end rot (Miller *et al.*, 1991).

Mango fruit apparently have the capacity to recover from vapour-heat quarantine treatments (Mitcham and McDonald, 1993). Carbon dioxide content in vapour-heated fruit (46 °C for 180 or 240 min and 48 °C for 300 min) accumulated to 13% and O_2 decreased to 6% in the internal atmosphere. Ethanol, methanol, and acetaldehyde concentrations increased, electrolyte leakage increased and ethylene-forming enzyme activity decreased immediately after vapour heat treatments. However, 3 days after treatment, ethylene forming enzyme activity recovered and electrolyte leakage decreased to control levels. Vapour-heat treatment also reduced the rate of fruit softening and mesocarp colour development.

Modified and controlled atmospheres

Mango fruit is tolerant of insecticidal atmospheres (atmospheres with $< 1\%$ O_2 and/or $\geq 50\%$ CO_2) (Yahia, 1993; 1994; 1998a; Yahia and Tiznado, 1993; Yahia and Vazquez, 1993). 'Keitt' mango fruit tolerated up to 5 days in atmosphere containing as low as 0.2 kPa O_2 and as high as 79 kPa CO_2, at 20 °C. A treatment was suggested to control of *A. ludens* and *A obliqua* consisting of 0.5 kPa O_2 and 50 kPa CO_2 for

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260 min (Yahia and Ortega, 2000). Shrink wrapping has not been effective in the disinfestation of mango fruit of immature fruit fly, because the time needed to disinfect Florida-grown mangoes infested with Caribbean fruit fly eggs and larvae was reported to exceed the shelf life of wrapped mangoes (Gould and Sharp, 1990).

Irradiation

Irradiation involves the use of ionizing energy such as gamma rays, x-rays, electrons, and microwaves. The use of irradiation for fresh horticultural crops at a maximum dose of 1.0 kilogray (KGy) was approved by the US Food and Drug Administration for food in 1986. The mainland US has begun to use irradiation as a quarantine treatment for some fruits imported from Hawaii since April 1995, and some other countries, including Mexico, are currently irradiating mango for quarantine purposes. However, there are still several problems with the application of this treatment. Irradiation is unique among quarantine treatments in that it is the only treatment used which does not cause acute mortality; instead, insects are prevented from maturing or are sterilized. Irradiation dosage that kills insects and eradicates diseases can also damage the fruit (Yahia *et al.*, 2006a). Gamma irradiation has been tried in mango to control ripening, diseases and insects. For example, doses of 1.8 to 2.4 KGy can kill fruit flies or prevent the normal completion of the next successive life stage, but such high dosage is damaging to all fruits and vegetables (Yahia *et al.*, 2006a). Mango may suffer from doses as low as 150 Gy when applied on a commercial scale where much of the fruit load may receive doses of more than 300 Gy. The fact that insects are still alive for some time after irradiation has been one of the major obstacles to its use. Tephritids have been the most studied group of quarantined pests as far as irradiation is concerned (Hallman, 1999). Minimum absorbed doses confirmed with large-scale testing to provide control to the probit 9 level (99.9968%) have ranged from 50 to 250 Gy (Hallman, 1999). Dosage of 0.15 to 1.0 KGy can disinfest fruit flies in mango by allowing the emergence of only sterile adults (Yahia *et al.*, 2006a). The percentage of decayed mango fell when the fruit were irradiated with 750 Gy or higher, but fruit peel injury in the form of scald-like symptoms was observed with irradiation doses over 500 Gy (Spalding and von Windeguth, 1988) and at doses of 750 Gy (Thomas and Janave, 1973). The International Consultative Group on Food Irradiation has recommended 150 Gy as a minimum dosage for treating eggs and larvae of tephritidae fruit flies to prevent emergence of normal adults and has adopted 300 Gy as a generic disinfestation to sterilize any adults or emerging from treated larvae or pupae. Irradiation was reported to be effective against mango weevil infesting the seeds of the fruit (Burditt and Seo, 1971).

A dose of 76 Gy was effective in disinfesting mangoes of the Caribbean fruit fly eggs and larvae (Von Windeguth, 1986). Third instar Mediterranean fruit fly larvae in Mexican mangoes irradiated with 250 Gy did not emerge from pupae, and irradiation of third instar *A. serpentina* (Wiedemann), *A. ludens* and *A. obliqua* in Mexican mango with a dose of 60 Gy prevented adult emergence (Bustos *et al.*, 1992). Eggs and larvae of Queensland fruit fly and *Bactrocera jarvisi* (Tryon) in 'Kensington' mangoes were disinfested with 74–101 Gy (Heather *et al.*, 1991).

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Dielectric heating, a type of irradiation using microwaves, used for 'Pairi' mangoes at 2450 MHz and about 70 W, killed 99% of mango weevils when a mean internal seed temperature of 74±24 °C was reached (Seo *et al.*, 1970).

22.9 Postharvest handling practices

22.9.1 Harvest operations

Mangoes can be harvested any time after the fruit have reached their final, full size. As previously mentioned, while immature fruit have a flat shape in profile, with shoulders that slope down below the pedicel insertion, mature fruit have full cheeks and raised shoulders at the stem end. However, the time of harvest is determined by a combination of factors, including market demand, labour availability, shipping company schedules, anticipated shipping times and consumer preferences in the selected market. In some cases, it may be desirable to store mangoes after harvest and prior to shipping rather than to delay harvest, but it is never desirable from a quality standpoint to harvest prior to full maturity in an attempt to take advantage of market conditions. The harvest should be scheduled for the cooler parts of the day in order to reduce the incidence of heat injury and sunburn in the field, and to reduce energy costs associated with cooling. Rough handling should be avoided to reduce skin injuries and internal fractures and bruises. The fruit is picked by hand or with appropriate picking poles with attached bags or baskets, or an attachment to grip the fruit stem (Fig. 22.4).

Fig. 22.4 Harvesting and collection of mango.

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The fruit should never be cut or allowed to fall to the ground. Leaving a few centimetres of stem attached to the fruit when picking will keep the sap (latex exudates) from spurting out, but the long stems will eventually need to be removed because they may cause damage to other fruit in field bins during transport to the packinghouse.

When a mango fruit is detached from its stalk, or when the skin of an unripe fruit is cut, transparent liquid oozes out (Fig. 22.5). It has been suggested that the sap has a protective function, serving to repel fruit flies. The sap contained in the fruit is under considerable pressure. When the pedicel is broken the sap is exuded towards the fruit skin. Latex exudates (sap), with low pH and high oil content, can stain the fruit, burn the fruit skin and reduce its quality (Yahia *et al.*, 2006a) and prevent the development of ideal fruit colour. Areas of skin damaged by latex may develop bacterial or fungal legions, and latex-burned skin can be invaded with *Aspergillus spp.*, especially in hot conditions (Yahia *et al.*, 2006a). It has been reported that fruit skin damage by sap burn is particularly severe with 'Kensington', and less serious in Florida cultivars (Yahia *et al.*, 2006a). O'Hare (1994) found that latex levels were lower and less phytotoxic in 'Nam Doc Mai', Nang Klang Wun', 'Tong Dum' and 'Keow Savoey' (0.16–0.48 ml per fruit) than in 'Kensington' (1.67 ml per fruit). The oil component of the latex of the Thai cultivars was found to be much lower than that in 'Kensington'. The problem is aggravated if the fruit is picked in the early morning, and the peduncle is completely detached. It is recommended that fruit is picked when it is less turgid and latex flow is minimal. In addition, as mentioned earlier, it is important that at least 2 cm of peduncle be kept attached upon cutting of the fruit. High nitrogen content in the fruit has been associated with more severe latex burn.

Studies on 'Kensington' and 'Irwin' mango cultivars indicated that sap could be separated into two phases during centrifugation (Joel, 1980; Robinson *et al.*, 1993). The aqueous phase was milky and viscous and contained mainly proteins and polysaccharides, while it was the non-aqueous phase which was

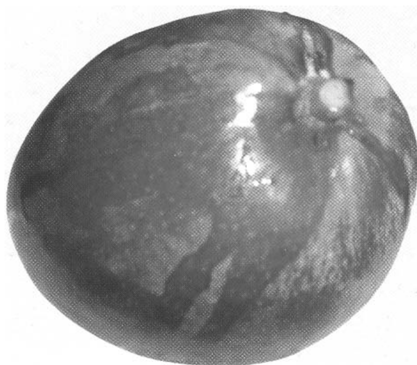

Fig. 22.5 Latex exudates on mango fruit.

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yellow-brown in colour with oily consistency that predominantly caused skin damage. However, Underhill and Dahler (1995) described four types of skin browning caused by components of the oil phase of the latex with symptoms distinct from the sap burn. The browning symptoms were due to reactions with PPO from the aqueous phase of the latex. Blackening of the fruit skin caused by latex usually appears over the course of a few days. Both sap and skin of mango fruit have considerable PPO activity. However Robinson *et al.* (1993) concluded that browning of mango skin induced by the sap is predominantly catalysed by PPO in the skin and that this is unlikely to be prevented by heat treatments of the fruit. The sap enzyme was not activated. Sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS) was inhibited by hexadecyltrimethylammonium bromide, and was active with both para- and ortho-diphenol substrates. The skin PPO was activated by SDS, was inhibited by salicylhydroxamic acid and polyvinylpyrrolidone, and was active only with ortho-diphenol substrates. These properties suggested that sap PPO is a laccase-type enzyme whereas the skin contains the more common catechol oxidase-type PPO. The skin enzyme had a temperature optimum of 30 °C but the sap enzyme had maximum PPO activity at 75 °C. Both enzymes were relatively thermostable, requiring more than 15 min at 80 °C for 50% loss of activity.

Mango latex is also known to cause allergic dermatitis (Yahia *et al.*, 2006a). Patients have developed urticaria and eczematous rash following exposure to mangoes. Patch testing with diluted sap, crushed leaf, crushed stem and fruit skin was strongly positive. It has been suggested that the allergic material in mango is 5-[2(Z)-[heptadecenyl] resorcinol (Bandyopadhyay *et al.*, 1985). However, terpinolene is the major component of the oily phase of sap contained in the fruit of 'Kensington' mangoes and 3-carene the important component in the sap of the fruit of 'Irwin' mangoes (Loveys *et al.*, 1992). Synthetic terpinolene gave indistinguishable sap burn symptoms from mango latex when applied to mango fruit surface (Loveys *et al.*, 1992). According to Loveys *et al.* (1992), terpinolene in the latex of 'Kensington' fruit, and not –(12-heptadecenyl)-resorcinol, is the main cause of skin burn. Harvesting and packinghouse personnel should avoid contact with the latex and workers who are allergic to mango latex should be assigned to other duties.

Several strategies have been suggested to combat the problems caused by latex, including harvesting of the fruit with the pedicel attached, inversion of the fruit to allow the sap to drain until the pedicel dries and the use of detergents and emulsions which reduce the effects of the sap (Yahia *et al.*, 2006a). Some of the suggested methods include:

- Desaping in a 1% solution of calcium hydroxide. This is not used commercially.
- Washing fruit in 1% aluminum potassium sulfate.
- Applying a surface coating to fruit prior to eliminating the latex (de-saping).
- Trimming and de-saping at the packinghouse followed by inversion on a stationary rack or a roller-conveyer running below water or water and detergent sprays for 20 minutes.

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- Soil bleeding: inversion in the soil at a shady spot immediately after harvest for 30 minutes. This is commonly used in some countries like Egypt, but causes a significant increase in the incidence and earlier appearance of stem-end rot, resulting from soil-borne microflora.

Dipping 'Kensington' mango fruits in DC Tron® at 100 mul L^{-1} for 30 to 60 s resulted in the highest levels of sap burn control, when compared to similar levels of other paraffinic oils (Lim and Bowman, 1995). Spraying fruits in crates resulted in poor coverage and poor sap burn control. However, DC Tron® at 750 mul L^{-1} used as non-recirculating, agitated spray on a conveyor system resulted in good control of sap burn and would be suitable for large scale commercial use due to negligiable sap contamination of the machinery.

22.9.2 Packinghouse practices

Harvested fruit should be transported to the packinghouse or to the market as soon as possible. Exposure to the sun in the field, on the road, in the packinghouse, or in the market should be avoided. The incidence of internal breakdown in 'Alphonso' mango fruit exposed to the sun, after as little as 5 min from harvest, was 5% greater than the control, and 100% of the fruit developed the symptom after ripening (Yahia *et al.*, 2006a). Fruit should be transported with care so that mechanical injury is minimal. Drivers should use well-surfaced roads, vehicles tyres should be correctly inflated, and vehicle suspension should be in good condition.

At the packinghouse, if there is a delay before packing, the fruit should be set in a shed and be protected from the sun, high temperature, wind, rain, etc. Fruit should be packed within no more than 3–4 hours from arrival. It is preferable that the peduncle be cut at this point to leave about 0.5 cm. Samples should be taken to evaluate the quality of the fruit. This inspection point is very important to determine the condition of the fruit, determine acceptance, the suitability for a determined market, the treatments that the fruit should receive in the packinghouse, decide the price on basis of quality evaluation, etc. If an infestation quarantine treatment is needed, a sample should be evaluated for the presence of insects.

It is recommended that fruit be received in water (Fig. 22.6) and transported on a roller conveyer to the other stages of the packinghouse process. The water may contain up to 200 ppm chlorine and fruit should be exposed for 3–5 seconds. Chlorine is degraded easily and thus its concentration should be monitored regularly. Fruit should be dried by air fan and/or using brushes. The packing line should be designed so that it can be comfortable for workers and will not damage the fruit (see Plate XL). Light and temperature should be controlled adequately (Yahia, 2005; Yahia *et al.*, 2006a).

Fruit should be selected, and only good quality fruit should be packed. The purpose of this step is to sort fruit into uniform categories (according to size, shape, colour and absence of defects), and to divert low quality fruit to another

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Fig. 22.6 Washing of mango fruit in the packinghouse.

use such as low quality market or processing. Fruit can be classified in different grades according to the requirements of the market. Damaged fruit should be removed. This is done manually by trained persons. Mango fruit can be classified manually, but uniformity will be much better when sizing is done mechanically either by size or weight according to the requirements of the market. Sizing can be done by using divergent arms, where the distance is minimal at the beginning and increases continuously. Distances between arms are adjustable so that fruit sizes can be modified depending on the cultivar and the requirement of the market. Small fruits are dropped at the beginning and biggest fruits are dropped at the end. These sizers are commonly used to classify mango fruit for the different hot water quarantine treatment. Weight sizers consist of plates controlled electronically, and each plate carries one fruit. When the fruit is dropped in the sizing plate, its weight is recorded, and the fruit will be dropped automatically in the packing band to which its size corresponds.

Waxing, which involves the coating of fruit skin with a thin layer of wax, can be beneficial as a barrier to mass transfer (water vapour and gases), can improve visual appearance of the fruit, and can provide an internal modified atmosphere (Yahia, 2005). This is especially beneficial when the fruit is treated with something (such as hot water) that can cause the bloom of the fruit to deteriorate after harvest. However, inadequate application of waxes can result in fermentation of the fruit, and therefore waxing of mango is not commonly used, mainly because of the risk of off-flavour development. Waxing was recommended for 'Kensington' mangoes in Australia to reduce sap burn (Shorter and Joyce, 1994). The use of light waxes

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is preferred to heavy waxes which can hamper colour development. Coating mango with a paraffin wax emulsion (7% solids) resulted in increased shelf-life (Mathur and Srivastava, 1955), especially in refrigerated storage (Bose and Basu, 1954). Coating with refined mineral oil, on the other hand, resulted in fruit injury (Mathur and Srivastava, 1955). This is probably due to the fact that oil coating decreases respiration more than the wax coating, thus resulting in anaerobic conditions and fruit injury. The dipping of immature green mangoes in 1.7–2.7% aqueous emulsion of a fungicidal wax, terpene resin, oleic acid and triethanolamine increased retention of ascorbic acid and moisture, and delayed fruit ripening and extended shelf-life (Mathur and Subramanyam, 1965). Coating with 7% wax emulsion containing a fungicide caused a 12.5% increase in cold storage life and a 66 to 100% increase in storage life in 'Neelum', 'Pardi', and 'Totapuri' mangoes (Mathur and Srivastava, 1955). A 6% wax-free shellac solution containing 0.25% diphenyl on 'Neelum' mangoes reduced fruit losses and delayed ripening after storage (Srivastava, 1959). The application of a 2.7% aqueous emulsion of a fungicidal wax containing 0-phenylphenol was reported to cause a 50% increase in storage life of 'Badami' mangoes at 26–30C and 55–87% RH (Mathur and Subramanyam, 1965). A wax emulsion of 6% solids with 250 ppm maleic hydrazide or 20 ppm 2,4-dichlorophenoxyacetic acid (2,4-D) delayed ripening of mango fruit compared with fruit treated with the same wax with no growth regulators (Subramanyam *et al.*, 1962).

Coating, by dipping in melted paraffin at 80 °C for 10s, was reported to reduce the rate of respiration and transpiration in 'Fazli' mangoes and prolonged the storage life at 10 °C and 90% RH for up to 42 days (Bose and Basu, 1954). Emulsion contained maltodextrins, sodium carboxymethylcellulose, propyleneglycol, and a mixture of sorbitan fatty acid esters sprayed on unharvested, fully mature, unripened 'Manila' mangoes and then fruit were harvested and stored at 15 °C or 25 °C and 80% RH, reduced weight loss, respiration rate and prevented penetration and proliferation of spoilage microorganisms without having an adverse effect on chemical composition. A shellac wax formulation that was recommended in South Africa as an alternative to polyethylene waxes was reported to cause severe retardation in skin colour (Milne, 1994).

When waxes are intended to be applied, it is important to investigate the regulation of the imported country regarding types of waxes allowed, but it is always preferable that these be of natural origin. The application of edible coating on minimally processed 'Arumanis' mango fruit slowed respiration rate and decreased the rate of quality changes (Purwadaria and Wuryani, 2000). If to be used, the wax should be applied in a thin uniform film, preferably using roller brushes, or a wax applicator, or by very light hand application. Dipping fruit in a wax emulsion is not recommended. The wax can be applied together with the fungicide. The fruit should be completely dry before applying the wax, otherwise foaming of water-emulsion waxes may occur.

Packaging is done manually. Exported fruit are commonly packed in a single layer in corrugated boxes (Fig. 22.7–22.9). Size and weight of packages depend on the requirements of the importer, but mango is commonly packed in boxes

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Fig. 22.7 Mango package (courtesy of Prof. Adel Kader).

Fig. 22.8 Mango packages.

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Fig. 22.9 Clamshell for six 'Ataulfo' mangoes (courtesy of Prof. Adel Kader).

with a capacity of 4 to 6 kg. There are tendencies for recycling and standardization. Packages made of mixed products are to be avoided. Also to be avoided are stapled products. Waxed packages, acceptable in the US and other markets, may not be acceptable in the EU market because they are not recyclable.

Palletizing allows much easier, faster, and uniform handling, lower costs, and better utilization of space in the storage rooms or transport containers. Pallet dimensions can be different in different markets, and thus should be investigated before shipping.

22.9.3 Ripening and its control

Ripening changes in mangoes can occur at temperatures from about 10 to 30 °C, although the overall rate as well as the rate of individual ripening parameters vary (Yahia *et al.*, 2006a). Colour development has been reported to be best at around 16 °C, while flavour development is best at around 27 °C. The best compromise temperature for optimum ripening of mangoes is usually about 20 to 22 °C. As a climacteric fruit, mango ripening can be initiated and coordinated by treatment with ethylene. Application of about 100 ppm ethylene for 12 to 24 hours at 20 to 22 °C and 90 to 95% RH will give the best results in terms of maximum ripening acceleration and quality. Ethylene-treated fruit will be more uniform in ripening stage and appearance. It is possible to initiate ripening either prior to shipping or at the receiver. As mentioned above, ripening initiated fruit will be somewhat more difficult to handle successfully over long shipping periods because of the difficulty of controlling ripening, but can be shipped at a lower temperature than unripe fruit.

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22.9.4 Recommended storage and shipping conditions

Mango fruit destined for storage or long distance shipping should always be precooled. Pre-cooling is very important to absorb field heat, to slow the rate of various biochemical and physiological processes within the fruit, and to decrease the refrigeration demand during cold storage or refrigerated transport. Rapid cooling is necessary for maximum quality retention and shelf life. Mango is commonly precooled by forced-air cooling, which is commonly done after packing and packaging (Yahia, 2005; Yahia *et al.*, 2006a). Any delays between harvesting and cooling will result in some loss of shelf life and quality. Such delays may be critical for certain handling scenarios that involve, for example, long shipping distances or very demanding buyers. Cooling to the storage temperature within 24 h of harvest and within 8 h of packing are achievable and worthwhile goals for any mango handling operation. Mature green mangoes should not be stored or shipped below about 12 °C. As the fruit ripen, lower temperatures may be safely used. Tree ripe mangoes can be safely handled at 8 °C (Yahia, 2005). Mango fruit should be maintained at high (85–90%) RH. Lower RH will promote water loss, shriveling, uneven ripening and quality deterioration. Mango is not commonly stored for prolonged periods. However, after pre-cooling the fruit should be moved immediately to the cold room or to the refrigerated transport container.

22.10 Processing

22.10.1 Fresh-cut

Mango is a very suitable fruit for production of fresh-cut items, and a fresh-cut mango industry is developing in several countries. The quality of the intact fresh fruit is important for the quality of fresh-cut items. Important factors include cultivar, preharvest cultural practices and climatic conditions, maturity at harvest, harvesting method, postharvest handling procedures, time between harvest and preparation of the fresh-cut product, method of preparation (sharpness of the cutting tools, size and surface area of the cut pieces, washing, and removal of surface moisture), and subsequent handling conditions such as packaging, speed of cooling, maintaining optimum temperature and RH, expedited marketing, and proper sanitation procedures. Mangos must be ripened, at least partially, before cutting to ensure better flavour quality in the fresh-cut products. 'Yellow flesh colour' and 'no green colour remaining' were the optimum maturity stages for production of fresh-cut items in terms of maintenance of acceptable appearance, texture, and taste in 'Tommy Atkins', 'Haden' and 'Palmer' mangoes. Fresh-cut items from riper fruit developed flesh breakdown and browned more (Limbanyen *et al.*, 1998). Post-cutting life of fresh-cut mango at 5 °C was 8 to 10 days and was limited by flesh browning and softening. Peeling to a depth of at least 2 mm and trimming flesh near the stem was necessary to minimize browning (Limbanyen *et al.*, 1998). Partially ripe 'Kent' mango slices continued to ripen after cutting, but did not reach the same level of ripeness as whole mangoes did after 5 to 7 days

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at 13 °C or 23 °C (Tovar *et al.*, 2000). Fresh-cut slices made from half-ripe (12.5 to 14% SSC) and firm-ripe (14.5 to 17% SSC) 'Julie' and 'Graham' mangoes had a shelf life of 8 days at 5 °C or 4 days at 10 °C, and half-ripe (13–16% SSC) mangoes were ideal for fresh-cut in terms of maintenance of acceptable appearance, texture, and taste during post-cutting life at 5 °C (Allong *et al.*, 2000). Rattanapanone *et al.* (2001) recommended that 'Tommy Atkins' and 'Kent' mangoes should be 13 to 27 N firmness when cut to have an acceptable quality and reasonable shelf life as a fresh-cut product. Marketability was limited by development of watery condition, slight darkening, and microbial growth on the cubes. Beaulieu and Lea (2004) compared volatile and quality changes in stored fresh-cut mango cubes prepared from firm-ripe (86–92 N and 9–10% SSC) and soft-ripe (27–29 N and 12.5–14% SSC) 'Keitt' and 'Palmer' mangoes. Most soft-ripe cubes were unmarketable by day 7 at 4 °C. The firm-ripe cubes, however, were not ripe enough to produce an optimum product for consumers, even though their storage-life was longer than that of the soft-ripe cubes. Fresh-cut 'Tommy Atkins' mango had a shelf life of 10 days at 3 °C, and that naturally ripened mango presented the best flavour and consumer preference compared with mature-green mangoes that were ripened with ethylene for 12 h at 25–30 °C before cutting (DeSouza *et al.*, 2005).

Hot water quarantine treatment of whole mangoes did not significantly affect the quality of fresh-cut 'Kent' mango slices stored at 5 °C (Dea *et al.*, 2008), but if treatment temperature and/or duration exceed the assigned one resulting in fruit heat damage, the mangoes will not be adequate for fresh-cut processing. Cooling after heat treatments reduces heat damage. Djioua *et al.* (2009) reported that hot water treatment at 50 °C for 30 min was optimal for fresh-cut 'Keitt' mango. Washing whole 'Chok Anun' mangoes in warm (50 °C) or cold (12 °C) chlorinated water at 200 ppm for 5 minutes significantly reduced total microbial populations on the skin and stem end of the mangoes (Ngarmsak *et al.*, 2005).

The use of very sharp tools to peel mangoes and cut the flesh reduces cellular damage and leakage of cellular contents and enzymatic browning. Packaging in rigid containers reduces water loss and mechanical damage during distribution. Peeling and cutting (wounding) of mango seem to have a minor effect on the physiology of fresh-cut mangoes. Storage of fresh-cut 'Julie' and 'Graham' mangoes at lower temperatures (5 °C compared to 10 °C) reduced the negative effects of wounding, including the level of microbial contamination (Allong *et al.*, 2001).

Shelf life of fresh-cut mango cubes is limited by softening and browning. Shelf lives of mango cubes treated with distilled water (control), 0.5% $CaCl_2$ and 1% $CaCl_2$ and maintained at 5 °C were about 5, 7 and 9 days, respectively (Chantanawarangoon, 2000). Mango cubes treated with 1% $CaCl_2$ had higher firmness and calcium content than those treated with 0.5% $CaCl_2$ or water. It was suggested that the most suitable conditions for quality preservation of fresh-cut 'Tommy Atkins' mango were dipping in a solution of 3.5% (w/w) $CaCl_2$ at 35 °C for 20 min and packaging in MA (5 kPa O_2 + 5kPa CO_2) (Trindade *et al.*, 2003). MA (10 kPa O_2 + 10 kPa CO_2) slowed browning and softening of fresh-cut

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mangoes as compared to control, which was kept in air (Limbanyen *et al.*, 1998). The visual quality of 'Haden', 'Keitt', and 'Kent' mango cubes stored in 2 kPa O_2 + 10 kPa CO_2 was much better than those stored in 2 kPa O_2 or air + 10 kPa CO_2 or in air (control), all at 5 °C (Chantanawarangoon, 2000). Mango cubes dipped in 1% $CaCl_2$ and stored in 2 kPa O_2 + 10 kPa CO_2 had a shelf life of 12 days compared to 9 days for those dipped in 1% $CaCl_2$ and stored in air, and rate of softening was slowest in mango cubes stored in 2kPa O_2+10 kPa CO_2 (Chantanawarangoon, 2000). It has been reported that fresh-cut 'Tommy Atkins' mango cubes can be held in 0.5 to 4.0 kPa O_2 at 5 °C (Rattanapanone and Watada, 2000). The marketable period of fresh-cut 'Tommy Atkins' and 'Kent' mango cubes was 3 to 5 days at 10 °C or 5 to 8 days at 5 °C and was extended by 1 to 2 days when cubes were held in 4 kPa O_2 + 10 kPa CO_2 or 2 kPaO_2 + 10 kPa CO_2 (Rattanapanone *et al.*, 2001). However, while CA was beneficial in maintaining quality of the cubes, temperature was more effective. 'Keitt' mangoes harvested at 7–8% SSC and kept at 13–15 °C until their SSC reached 11–12% before preparation of the cubes, and packaged in 4kPa O_2 + 10 kPa CO_2 had the longest shelf life of 25 days at 5 °C in comparison with vacuum packaging, 100 kPa O_2, and air control (Martinez-Ferrer *et al.*, 2002). It has been suggested that the shelf life of fresh-cut mangoes could be extended by packaging in PET containers (Chonhenchob *et al.*, 2007). The shelf life of fresh-cut 'Carabao' mangoes was 6 days at 5 °C and 4 days at 13 °C, and 10 kPa CO_2 enhanced texture and reduced bacterial count (Poubol and Izumi, 2005a;b).

Mango cubes treated with 1% $CaCl_2$ + 1% ascorbic acid + 0.5% L-cysteine, 1% $CaCl_2$ + 1% citric acid + 0.5% N-acetylcysteine or 1% $CaCl_2$ + 1% ascorbic acid had higher visual quality scores than those dipped in water (Chantanawarangoon, 2000). It has been suggested that 1%$CaCl_2$ is important for maintaining firmness and extending shelf life of fresh-cut mango cubes, but if the marketing period is longer than 6 days additional chemicals, such as 1% ascorbic acid + 0.5% L-cysteine or 1% citric acid + 0.5% N-acetylcysteine, should be applied in addition to 1% $CaCl_2$ in order to delay browning (Chantanawarangoon, 2000). Fresh-cut 'Tommy Atkins' mangoes dipped for 30 sec in 5 ppm chlorine dioxide, 2% calcium ascorbate and 0.5% N-acetyl-L-cysteine or coated with 1% carboxymethylcellulose (CMC) or CMC and 0.5% maltodextrin (CMM) maintained good visual quality for up to 21 days at 5 °C or 14 days at 10 °C (Plotto *et al.*, 2004). Treatment of fresh-cut mangoes with antioxidants to prevent colour darkening in storage is necessary, and it has been reported that the most effective chemical treatment to reduce browning, softening, and decay of fresh-cut 'Namdokami' mangoes was 0.1 M ascorbic acid (Chonhenchob *et al.*, 2007). Treatment with 1% $CaCl_2$ + 1% ascorbic acid + 0.5% L-cysteine for 2 min approximately doubled the reduced ascorbic acid (RAA) and total ascorbic acid (TAA) concentrations in mango cubes (Chantanawarangoon, 2000). During 10 days of storage at 5 °C, there were no significant changes in RAA, dehydroascorbic acid (DHAA), and TAA concentrations of mango cubes in control and those treated with 1% $CaCl_2$ and stored in CA, but RAA and TAA contents of mango cubes treated with 1% $CaCl_2$ + 1% ascorbic acid + 0.5% L-cysteine and kept in air or CA declined, while DHAA increased during storage.

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Storage in 2 kPa O_2 + 10 kPa CO_2 was effective in maintaining TAA by slowing the oxidation of RAA to DHAA (Chantanawarangoon, 2000). Mango cubes treated with 1% $CaCl_2$ + 1% ascorbic acid + 0.5% L-cysteine and stored in air or CA for 17 days had lower β-carotene than those stored for 10 days (Chantanawarangoon, 2000). Fresh-cut 'Ataulfo' mango cubes maintained for up to 9 days at 5 °C had less ascorbic acid and total carotenoids and slightly less phenolics (Gil *et al.*, 2006). Robles-Sanchez *et al.* (2007) suggested that low temperature and MA/CA can preserve quality and antioxidant capacity of fresh-cut mangoes for up to 10 days. Exposure to ultraviolet C (UV-C) radiation for 10 min increased phenolics and flavonoid contents of fresh-cut 'Tommy Atkins' mangoes stored for 15 days at 5 °C, but reduced vitamin C and carotenoids contents (Gonzalez-Aguilar *et al.*, 2007).

Sanitation of the whole fruit and the processing plant and maintaining a low temperature environment during all fresh-cut process is important to reduce potential microbial problems. Surface sterilization with 80% ethanol before peeling followed by storage in 1.5 kPa O_2 and 11 kPa CO_2 in sealed LDPE bags totally inhibited microbial spoilage of peeled mango pieces for 3 weeks at 5 °C (Thambaramala, 1997). Treatment with 1% $CaCl_2$ + 1% ascorbic acid + 0.5% L-cysteine was effective in reducing microbial growth on fresh-cut mango cubes for up to 10 days in air and for up to 17 days in 2 kPa O_2 + 10 kPa CO_2 at 5 °C (Thambaramala, 1997). The use of 100 ppm peroxyacetic acid to sanitize whole 'Keitt' mangoes followed by a 30-sec dip of cut slices in peroxyacetic acid (50 ppm) or acidified sodium hypochlorite (200 ppm) effectively reduced microbial growth and kept microbial counts low on cut fruit surfaces for 21 days when compared to cut fruit slices from 200 ppm sodium hypochlorite-treated whole mangoes (Narciso and Plotto, 2005). Treating fresh-cut mangoes with 80 mM vanillin solutions before packing and storage at 5 °C or 10 °C significantly delayed the growth of spoilage yeast and fungi in fresh-cut mangoes (Ngarmsak, 2007).

Treatment of whole 'Kent' mangoes with 1-methylcyclopropene (1-MCP) and heat treatments (38 °C and 98% RH for 12 or 24 h) decreased firmness in fresh-cut product, while ethanol (5 g kg^{-1}) treatment maintained firmness similar to the control (Plotto *et al.*, 2003). Vilas-Boas and Kader (2007) also reported that softening and browning were delayed with application of 1-MCP (0.5 or 1.0 ppm for 6 h) directly on fresh-cut 'Kent' and 'Keitt' mango slices maintained for 9 days at 5 °C. Combinations of antibrowning agents and modified atmosphere packaging (MAP) reduced browning and deterioration of fresh-cut 'Kent' mangoes stored at 10 °C for up to 14 days (Gonzalez-Aguilar *et al.*, 2000). High pressure processing (300 and 600 MPa for one min) of mango cubes maintained for up to 9 weeks at 3°C reduced mango flavour, prevented increases in microbial load, and increased off-flavour, but did not affect colour and other sensory attributes (Boynton *et al.*, 2002). Short osmotic dehydration using sucrose (65°Brix) at 30 °C under vacuum (211 mbar) and storage at 5 °C was suggested to extend the shelf-life of minimally processed 'Kent' mango slices for up to 20 days (Tovar *et al.*, 2001a;b).

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22.10.2 Other processing practices

Mangoes are processed into diverse products such as juices, nectars, jelly powders, fruit bars, flakes, dried products, jams, puree, dehydrated products and canned slices, among others (Mahayothee, 2005; Saeed and Khattab, 1974; Karla *et al.*, 1995). However, only about 0.22% of mangoes produced in the world are processed (Yahia *et al.*, 2006a). Edible pulp makes up to 33–85% of the fresh fruit, while peel and kernel amount to 7–4% and 9–40%, respectively (Wu *et al.*, 1993). Byproducts of industrial mango processing may amount to 35–60% of the total fruit weight. Mango pulp is produced extensively for different use, such as the preparation of juices, jams and other products. The pulp of sour and seedling varieties in India is traditionally dried in the sun on an extensive scale for use as an ingredient in Indian food preparations, such as to produce mango leather, where the Brix of mango pulp is raised to 25°Brix and acidity to 0.5% by adding sugar and citric acid, respectively. This pulp, after mixing with potassium meta bisulphate at 0.2%, is spread on aluminium or stainless steel trays to a moisture level of 18–20% in a cabinet drier at 55–60 °C. The dried material which has a leathery consistency is rolled and cut into pieces of convenient sizes. The pieces are then wrapped in polyethylene sheet and packed in friction top tins (Anon, 1990).

Several other parts of mango fruit are also utilized, such as for example, the mango kernels, which are a source of fat, natural antioxidants, starch, flour and feed (Arogba, 2002; Kaur *et al.*, 2004; Puravankara *et al.*, 2000). Studies have been conducted on the peel for possible use in the production of biogas (Madhukara *et al.*, 1993), dietary fibre with a high antioxidant activity (Laurrauri *et al.* 1996a;b), as a source of pectin, flavonol O- and xanthone C-glycosides (Berardini *et al.*, 2005a;b), gallotannins and benzophenone derivatives (Berardini *et al.*, 2004).

Green mangoes are processed into traditional products like pickle, brine stock and chutney. The stage of maturity of the whole fruit affects the quality of the finished products (Yahia *et al.*, 2006a). There are two classifications of pickles: salt pickles and oil pickles, processed from whole and sliced fruit with and without stones. Diverse types of pickles vary mainly in the proportions and kinds of spices used in their preparation. The ingredients are mixed together and filled into wide-mouthed bottles, and three days later the contents are thoroughly mixed and refilled into the bottles, and extra oil is added to form a 1–2 cm layer over the pickles (Yahia *et al.*, 2006a).

Chutney is prepared from peeled, sliced or grated mature or semi-ripe mango by cooking the shredded fruit with salt over medium heat for 5 to 7 min, when it is mixed and then sugar, spices and vinegar are added. Cooking is done over moderate heat until the product resembles a thick purée, and remaining ingredients are added and simmered for another 5 min, cooled and preserved in sterilized jars. Spices usually include cumin seeds, ground cloves, cinnamon, chili powder, ginger and nutmeg. Other ingredients such as dried fruits, onions, garlic and nuts may be added (Yahia *et al.*, 2006a).

Commercial beverages are juice, nectar and squash (Yahia *et al.*, 2006a). Mango nectar and juice contain mango purée, sugar, water and citric acid in

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various proportions depending on local taste, government standards of identity, pH control, and fruit composition of the variety used. In addition, mango squash may contain SO_2 or sodium benzoate as a preservative. Other food grade additives such as ascorbic acid, food colouring, or thickeners may be used in mango beverages. Mango juice is prepared by mixing equal quantities of pulp (purée) and water and adjusting the TSS and acidity (12 to 15% TSS and 0.4 to 0.5% acidity as citric acid). Ripe mangoes are dried in the form of pieces, powders, and flakes.

Drying procedures such as sun-drying, tunnel dehydration, vacuum-drying, or osmotic dehydration may be used. Packaged and stored properly, dried mango products are very stable and nutritious. Mango drying is very common in most production areas. Sun drying is the most common because it is inexpensive, but the product is susceptible to contamination by dirt, insects, rodents and microorganisms; the process requires several days according to availability of sunlight and temperature control is difficult. Other, more hygienic and equally cost-effective systems have been designed and used, including mechanical and solar dryers (Yahia *et al.*, 2006a). Currently, the use of vacuum for puffing and drying mango and similar food materials is not as widespread as explosion puffing (Eskew *et al.*, 1963), high temperature short time (HTST) pneumatic drying and centrifugal fluidized bed (CFB) drying (Brown *et al.*, 1972), because of high cost, but with the increasing consumer demand for high-quality processed foods and their willingness to pay a higher price for such products, vacuum-puff dehydration could become an economically viable investment opportunity in the mango processing industry (Raymundo *et al.*, 2009). The notably short drying time of this process can be a significant advantage (Candelaria and Raymundo, 1994). In this process, mango pieces are heated at a positive pressure of 40–50 kPa until the maximum tissue temperature of 100 °C is reached, usually within 8 min, and total dehydration time is about 6 h (Raymundo *et al.*, 2009). Pressure–temperature combinations provide desirable puff and rehydration characteristics (Candelaria and Raymundo, 1994).

Spray-dried mango powders are used for flavouring confectionery and pharmaceutical preparations as well as in the manufacture of baby foods and tropical fruit drinks fortified with nutrients to replace those portions lost during processing (Raymundo *et al.*, 2009). It has been suggested that spray-drying is by far the most cost-effective method for transforming fruit pulps into powder (Raymundo *et al.*, 2009). The purée of green mangoes can also be converted to a powder just like the purée of ripe mangoes by spray-drying, and spray-dried powder can be mixed with other condiments and used as a souring agent for some dishes, or as the raw material in the manufacture of instant green mango shake (UPLB, 2005).

Spray-dried instant green mango shake is popular, especially in Southeast Asia and elsewhere (Reymundo *et al.*, 2009). Finely diced fresh green mango pieces are mixed with water, sugar and ice to make a cheap, wholesome summer drink during the mango season, and the practice has been modified and upgraded to cater to upscale domestic markets and abroad (Reymundo *et al.*, 2009).

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22.11 Conclusions

Mango is a very important fruit in world trade. Key factors for the supply of high quality mango include: (1) harvesting fruit at the optimum maturity stage for the intended market; (2) careful handling to minimize physical injury; (3) treatments for decay control; and (4) storing and shipping at the optimum temperature and atmosphere to maintain high quality (Yahia, 2005; Yahia *et al.*, 2006a). Fruit are usually harvested at the mature-green stage, prior to ripening initiation, and stored and/or transported at low temperatures at or near the threshold for induction of CI. These practices may result in poor quality immature and chill-injured mangoes appearing on the market. Strategies used to extend mango postharvest life are based on control of ripening, ethylene production and action, and diseases. Adequately harvested and handled mango that have not yet started ripening can be shipped in MA/CA and maintained for up to 4–6 weeks at 8–12 °C and 85–90% RH. Successful handling of ripening-initiated mangoes is difficult due to the fruit's short shelf life and the increased incidence of internal breakdown that accompanies delayed harvests, making long distance transport of ripening mangoes almost impossible. Unfortunately the rapid expansion of the export market for fresh mangoes, which occured in the 1990s, has not continued. Future expansion will require better understanding of mango postharvest physiology and the development of adequate postharvest technologies. It is certainly worth investigating improved procedures for storage and ripening that would allow preconditioned, ripening-initiated, ready-to-eat mangoes to be offered to consumers. Genetic transformation of mango to manipulate the progression and uniformity of ripening and softening may be also a helpful strategy.

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(a)

(b)

Plate XXXVII (Chapter 21) Mamey sapote fruit sold in the street in Mexico.

Plate XXXVIII (Chapter 22) External and internal colour changes during ripening of 'Tommy Atkins' mango fruit.

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Plate XXXIX (Chapter 22) Changes in external and internal colour during maturation and ripening of mango.

Plate XL (Chapter 22) Mango packinghouse.

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Index

ABG–3161, 52
Acca sellowiana [Berg] Burret, 115–31
  culinary uses, nutritional value and health benefits, 119–20
    general feijoa fruit facts, 119
  cultivars and genetic variability, 118–19
  origin, botany, morphology and structure, 115–17
    flower and mature fruit on the tree, 117
    ripening index for feijoa fruit, Plate X
  postharvest crop losses, 127–9
    chilling injury, 127–8
    insect pests and their control, 129
    internal and external symptoms, Plate XI
    other physiological disorders, 128–9
    pathological disorders, 129
    physical damage, 128
  postharvest handling factors affecting quality, 125–7
    ethylene, 127
    fruit size grading, 125
    grading standards in Colombia, 126
    handling and grading, 125–6
    modified or controlled atmosphere, 126–7
    temperature and relative humidity, 126
  postharvest physiology and quality, 124–5
    respiration and ethylene production, 124
    ripening, quality components and ripening indices, 124–5
  preharvest factors affecting fruit quality, 120–3
    flowering and pollination, 120–1
    fruit growth and development, 121–2
    maturity and harvest, 122–3
    modern feijoa orchard, 123
    yield, 123
  processing, 129–30
  worldwide importance and economic value, 117–18
Acetobacter aceti, 29
Acetobacter bacteria, 59
Achradelpha mammosa see Pouteria sapota Jacq. H.E. Moore & Stearn
Achras mammosa L. *see Pouteria sapota* Jacq. H.E. Moore & Stearn
Acrostalagmus albus, 266
Actinidia spp., 326–53
  commercial practice, 348–53
    controlled atmosphere storage, 352–3
    degreening, 350–1
    harvest index, 349–50
    temperature management, 351–2
  future trends, 353
  maturation, 331–3
  physiological disorders, 341–3
    impact and compression damage, Plate XXV
    low temperature breakdown, Plate XXIV
  postharvest handling, 346–8
  postharvest pathology, 343–6
  postharvest physiology, 333–41
    low temperature responses, 339–41
    ripening other than softening, 338–9
    softening, 333–8

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vine and fruit, 327–31
fruit, 328–31
vine, 327–8
after-roast darkening, 467–8
air roasting, 466
alcohols, 88
Alphons *see Mangifera indica* L.
Alphonso *see Mangifera indica* L.
Alternaria rot, 526
Ameeri *see Mangifera indica* L.
American Society for Testing Materials, 37
1-aminocyclopropane–1-carboxylic acid (ACC), 85
Amrapali *see Mangifera indica* L.
amyloglucosidase (AMG), 176
Anastrefa fraterculus, 266
Anastrefa obliqua, 266
Anastrepha ludens, 529
Anastrepha ludens Loew, 230
Anastrepha obliqua, 529
Anastrepha suspense Loew, 230
anthocyanase, 371
anthocyanins, 365, 370, 371
anthracnose, 228, 376, 525
antioxidants, 457
aril necrosis, 97
artificial ripening, 307
Artocarpus heterophyllus Lam., 275–98
composition and nutritional value, 279–84
acidity and crude fibre, 280–1
biochemical constituents, 281
carbohydrate and fatty acid content, 281–2
changes during ripening and inter tree variability, 283–4
chemical composition, 283
phenolic content, 280
total soluble solids, 281
vitamins, minerals, amino acids and other constituents, 282–3
volatiles, 280
culinary uses, 278–9
economic value and overview of major uses, 277–8
jackfruit being sold in market, Plate XXII
fruit growth, respiratory behaviour and ripening, 279
medicinal value, 278
origin, botany, morphology and structure, 275–6
pathological disorders and insect pests, 288
postharvest handling practices, 284–7
details, 286–7
preharvest factors affecting fruit quality and harvest timing, 284
processing, 288–95
beverages, jam and fruit bars, 292–4
by-products, 294–5
dehydrated products, 291–2
dehydration process protocol, 293
fresh-cut processing, 288, 290
frozen products, 294
hurdle technology-based shelf-stable product, 290–1
minimal processing protocol, 290
process protocol for hurdle technology-based processing, 291
products from immature jackfruit, 294
utilisation of jackfruit as various products, 289
worldwide importance, 276–7
hard and soft pulp varieties, Plate XXI
Arumanis *see Mangifera indica* L.
Ashwini *see Mangifera indica* L.
Aspergillus flavus, 21
Aspergillus niger, 21
Aspergillus niger Van Tiegh, 60
Aspergillus nigri vars, 148
Aspergillus parasiticus, 60
Aspergillus rot, 187
Aspergillus rot, 526
Ataulfo *see Mangifera indica* L.
Avogreen, 391

Bacillus subtilis, 391
Bactrocera spp, 529–30
Badami *see Mangifera indica* L.
bagging, 313
Banganapalli *see Mangifera indica* L.
Bappakai *see Mangifera indica* L.
Batrocera correcta (Bezzi), 230
Beaumont guava, 218
beetle *see Necrobia rufipes* de Geer.
Bellary *see Mangifera indica* L.
Bengal *see Litchi chinensis* Sonn.
berry ripening, 183
Betocera rufomaculata, 288
Beverly *see Mangifera indica* L.
biocontrol agents, 388–9, 391–2
biodiesel, 37
bioelectrical resistance (BER), 170, 171
Bioriented Polypropylene (BOPP), 389, 390
black nose, 58
black rot, 60
bleaching, 188
blue mould *see Penicillium expansum*

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Bo-Erica, 327
Bosworth–3 *see Litchi chinensis* Sonn.
Botryodiplodia theobromae Pat, 60
Botryosphaeria, 345
Botrytis cinerea, 185–6, 431–2
Botrytis fuckeliana, 431–2
"Bou Faroua" disorder, 61
Bourbon *see Mangifera indica* L.
BoxiBag, 389
Breba crop, 140
Brewster *see Litchi chinensis* Sonn.
brown centres, 455
browning, 429–30
bruising, 128
bunch stem necrosis *see* waterberry

Cadra cautella, 21
caffeic acid, 87
calcium, 306
Calocarpum mammosum see Pouteria sapota Jacq. H.E. Moore & Stearn
Calyx-end fruit rot, 60
Cambiodiana *see Mangifera indica* L.
Canarium odontophyllum Miq., 34–9
  culinary uses, nutritional value and health benefits, 36–7
  harvesting, 37–8
    long bamboo pole with a sickle at the end is used, Plate V
  'Laja' and 'Lulong' clones
    fruit nutritional values, 36
    fruit physical characteristics, 36
  maturity and quality components and indices, 38
  origin, botany, morphology and structure, 34–6
    fruit panicles with white immature dabai fruit, Plate IV
  postharvest handling factors affecting quality, 38–9
    fruits after 7 days storage, 38
  postharvest physiology, 37
canopy position, 221–2
caprification, 137
  illustration, 138
Caprifigs, 137
Capulinia jaboticabae, 266
Carabao *see Mangifera indica* L.
Caribbean fruit fly *see Anastrepha suspense* Loew
Cecil *see Mangifera indica* L.
centrifugal fluidised bed (CFB) drying, 549
Ceratitis capitata (Wiedemann), 265, 529
Ceratitis cosyr, 529
Ceratitis rosa, 529
Ceylon Jack see Artocarpus heterophyllus Lam.
Champa Hazari see Artocarpus heterophyllus Lam.
Chandrakaran *see Mangifera indica* L.
Changhong 3 *see Eriobotrya japonica* L.
chico-mamey *see Pouteria sapota* Jacq. H.E. Moore & Stearn
chilling injury, 94
  cocona fruit, 4
  coconut, 20
  durian, 96
  feijoa, 127–8
  fig, 147
  golden apple, 169–71
  guava, 223, 227–8
  internal and external symptoms, Plate XI
  jaboticaba, 264
  litchi, 373
  loquat, 428–9
  mango, 523
Chinese jujube *see Ziziphus jujuba* Mill.
chitosan, 392–3
chlorine fertilisation, 17
Chuliang *see Dimorcarpus longan* Lour.
chutney, 548
Cladosporium rot, 187
Clysar EHC–50 copolymer film, 519
Clysar EHC–100 copolymer film, 519
Clysar EH–60 film, 519
cocona *see Solanum sessiliflorum* Dunal
coconut *see Cocos nucifera* L.
Cocos nucifera L., 8–30
  botany, morphology and structure, 8–9
    fruit shape and colour, Plate III
  dwarf cultivars, 8–9
  fruit biology and postharvest physiology, 11–12
    growth, development and maturation, 11–12
    respiration and ethylene production, 12
    ripening behaviour, 12
  maturity indices, 15–17
    trimmed young coconut fruit, 16
  origin, distribution, production area and trade value, 9–10, 11
    average annual export and import statistics (1961–2007), 11
    average annual harvested area, production and yield (1961–2008), 10
  physiological disorders and pests, 20–1
    mature coconut, 20–1
    young coconut, 20

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postharvest handling factors affecting quality, 18–20
atmosphere, 19–20
humidity, 19
physical damage, 18
temperature, 18–19
postharvest handling practices, 21–6
consumer table, 26
harvest operations, 21–2
packing house practices, 22–4
recommended storage and shipping conditions, 25–6
ripening and senescence control, 24–5
preharvest factors affecting quality, 17–18
cross pollination, 17
light, 17
maturity, 18
nutrients, 17
processing, 26–9
coconut gel (nata de coco), 29
coconut water, 28–9
copra, 26–7
desiccated coconut, 27–8
milk, 28
oil, 27
roasted coconut, 29
quality components, 12–15
fruit shape, kernel and liquid content, 12–13
moisture, sugar, acid and oil content, 13–14
other components, 14–15
tall cultivars, 8–9
use: fresh, processed products and nutritional value, 10–11
Codex Stan 184—1993, 512
CODEX Standard, 55–6
Colleototrichum gloeosporiodes, 129
Colletotrichum acutatum, 434
Colletotrichum gloeosporioides, 5, 228, 376, 377, 431
Colletotrichum gloeosporioides Penz., 20
Colocarpum sapota (Jacq.) *see Pouteria sapota* Jacq. H.E. Moore & Stearn
Common *see Mangifera indica* L.
Conotrachelus myrciariae, 266
controlled atmosphere, 126–7, 147, 154, 314–15, 436–7
controlled atmosphere storage, 226–7, 352–3, 395–6
copper hydroxides, 5
copra, 26–7
coumarins, 477
Cryovac D955, 519
Cryptorhynchus mangiferae, 530–1
cubiú *see Solanum sessiliflorum* Dunal
cumala *see Pouteria lucuma* (Ruiz and Pav.) Kuntze
CX STAN 177–1991, 27–8
CX-STAN 210–1999, 27
Cyptosporiopsis, 345

dabai *see Canarium odontophyllum* Miq.
Dasheri *see Mangifera indica* L.
date *see Phoenix dactylifera* L.
DC Tron, 539
defoliation, 4
Deglet Noor *see Phoenix dactylifera* L.
dehydration, 188–9
dessechement ed al rafle see waterberry
dielectric heating, 536
Dimorcarpus longan Lour., 408–19
arils of longan cv. 'Shixia,' Plate XXIX
fruit tree of longan cv. 'Shixia,' Plate XXVIII
marketing, 418
packaging, 415
postharvest characteristics, 409–12
composition, 409–10
ethylene evolution, 411
maturity, 409
nutritional composition per 100 g of longan fruit aril, 410
pathology, 412
peroxidative activity, 411
respiration, 411
texture, 410–11
ultrastructural changes, 411–12
postharvest handling, 412–15
fungicides, 413–14
handling system, 415
other handling technologies, 414–15
precooling, 412–13
recommendations for fungicide treatment, 413
recommendations for precooling, 413
sorting and grading, 412
processing, 418
storage, 416–17
ambient temperature, 416
low temperature, 416
modified and controlled atmospheres, 416–17
temperature recommendations for selected major cultivars, 416
transport, 417–18
export market, 417–18

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local market, 417
recommendations for transport and marketing, 417
Diplodia natalensis, 432
durian *see Durio zibethenus* Merr.
Durio zibethenus Merr., 80–109
distribution, production area and trade value, 81–2
production area and export volume in three leading producing countries, 82
fruit development and postharvest physiology, 82–6
growth, development and maturation, 82–5
respiration and ethylene production, 85
ripening behaviour, 85–6
width, length, weight and thickness during growth and development, 84
insect pests and their control, 99–100
internal insects, 100
surface insects, 100
maturity and harvesting indices, 88–93
days from anthesis, 89
dry matter content of aril, 89–91
fruit specific gravity, 92–3
fruit stem strength, 91
Monthong durians dry matter content, 90
sap sweetness from cut stem, 91–2
spine strength, 91
stem surface roughness, 91
swelling around abscission zone, 91
tapping sound, 89
maturity and quality components and indices, 86–93
antioxidant capacity, 87
fruit size and shape, 86–7
fruit stem, 87
lipid and pulp fibre content, 87
main volatiles in durians from three leading producing countries, 88
pigments, 87
volatiles, 88
origin, botany, morphology and structure, 80–1
fruit, cross section and dehiscence of durian, Plate VIII
Monthong durian cross section, Plate IX
pathological disorders, 98–9
Lasiodiplodia and others, 99
Phytopthora, 98–9
physiological disorders, 96–8
aril tip browning, 97
chilling injury, 96
Monthong durians firmness and uneven ripening score harvested from trees, 98
uneven fruit ripening, 97–8
water soaked core, 96–7
postharvest handling factors affecting quality, 94–6
atmosphere, 95–6
humidity, 95
others, 96
physical damage, 94
temperature, 94–5
postharvest handling practices, 100–6
controlled and modified atmosphere, 105–6
handling steps for durian exported from Thailand, 101
harvest operations, 102–3
packinghouse practices, 103
recommended storage and shipping conditions, 104–5
ripening and senescence control, 103–4
preharvest factors affecting fruit quality, 93–4
external factors, 93–4
internal factors, 93
rain and irrigation, 93–4
soil nutrients, 94
processing, 106–8
chip, 107–8
flour and powder, 108
fresh-cut durian, 106–7
frozen durian (pulp unit or whole fruit), 107
paste, 108
polyssacharide gel durian rind, 108
uses of fresh and processed products, and nutritional value, 82, 83
durian aril nutritional composition, 83
'Monthong' durian aril antioxidant capacity and penolic contents, 83

Earligreen, 327
easy let-downs, 464
electrolyte leakage (EL), 170, 171
endosepsis, 147, 148
Ephestia cautella, 21
Eriobotrya japonica L., 424–39
culinary uses, nutritional value and health benefits, 425–6
different processed produced, Plate XXXI

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fruit ripening and resistance based on molecular and proteomic levels, 438
fruits of different varieties, Plate XXX
integrative technologies for control of decay and chilling injury, 438–9
maturity and quality, 426–7
maturity characteristics, 426
quality characteristics, 426–7
nutrient compounds per 100 g of fruit, 425
physiological disorders, 428–31
browning, 429–30
chilling injury, 428–9
physical damage, 431
purple spot, 430–1
postharvest diseases, 431–2
Botrytis cinerea, 431–2
Colletotrichum gloeosporioides, 431
Diplodia natalensis, 432
Phytophthora palmivola, 432
Pseudomonas syringae, 432
postharvest physiology, 427–8
fruit physiological, physical and chemical changes, 427–8
respiration, ethylene production and ripening, 428
postharvest treatments, 432–4
decay control, 434
harvest operations, 432–3
packinghouse practices, 433
recommended storage and shipping conditions, 434
ripening and senescence control, 433–4
storage technologies, 435–8
controlled atmosphere conditions, 436–7
decay index and loquat fruit stored at CA for 50 days, 437
decay index and weight loss in different storage conditions, 437
hypobaric pressure storage, 437–8
low temperature storage, 435
modified atmosphere packaging, 435–6, 437
worldwide importance and economic value, 424–5
esters, 88
ethephon, 103, 106
ethylene, 37, 106, 127, 139, 152, 164, 165
ethylene diamine tetra-acetic acid (EDTA), 391
European Standard Organisation, 37
Ewais *see Mangifera indica* L.
Extreme *see Mangifera indica* L.
Fay Zee Siu *see Litchi chinensis* Sonn.
Fazli *see Mangifera indica* L.
feijoa *see Acca sellowiana* [Berg] Burret
Feizixiao *see Litchi chinensis* Sonn.
fermentation spoilage *see* souring
ficin, 136–7
Ficus carica L., 134–55
culinary uses, nutritional value and health benefits, 136–7
fruit development and postharvest physiology, 137–9
caprification, 138
development stages, externally and internally, Plate XII
growth, development and maturation, 138–9
morphology and types, 137–8
respiration and ethylene production, 139
response to ethylene, 139
harvested at two different maturity stages
'Brown Turkey' fig, 142
'Kadota' fig, 143
'Mission' fig, 143
'Zidi' fig, 144
insect pests and their control, 150
maturity, 142–4
internal differences at different stages, 142
'Panachee' fig harvested at commercial maturity, 144
quality components and índices, 140
origin, botany, morphology and structure, 134–5
pathological disorders, 147–9
fresh figs susceptible to decay, 148
physiological disorders, 147
postharvest handling factors affecting quality, 145–7
atmosphere, 147
delayed cooling effect on weight loss of 'Brown Turkey' and 'Kadota' fig, 146
fresh figs physical damage, Plate XIII
physical damage, 146
temperature management, 145–6
water loss, 146–7
postharvest handling practices, 150–4
'Brown Turkey' figs manual harvesting, 151
containers types for packing fresh figs, 153
fresh figs are harvested into small containers, 151

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harvest operations, 150–2
packing area, 152
packing figs at the side of field immediately after harvest, 153
packinghouse practices, 152
recommended storage and shipping conditions, 154
ripening and senescence control, 152–3
preharvest factors affecting fruit quality, 140–5
atmosphere, 147
Breba, 140–1
crops per year, 141
cultural practices, 145
fruit splitting, 141
genotype, 145
physical damages, 146–7
processing, 154–5
fresh-cut processing, 154
other processing practices, 154–5
respiration and ethylene production, 139
worldwide importance and economic value, 135
field packaging, 192
fig *see Ficus carica* L.
fig pollination *see* caprification
Fiji *see Mangifera indica* L.
filtration technique, 28
flavour reversion, 456
floating technique, 92
flower thrips, 188
foot rot, 310
forced air cooling, 194, 195, 196
forced hot-air quarantine treatments, 534
free fatty acids (FFA), 456–7
fruit rot, 60, 228
fruit softening, 333–8
fruit splitting, 191
fruit worm *see Neoleucenoides elegantalis*
fumigation, 62

gamma irradiation, 386
Generally Regarded As Safe compounds, 391
gibberellic acid, 104, 306
glacial acetic acid, 29
Goa *see Mangifera indica* L.
Golden *see Mangifera indica* L.
golden apple *see* Spondias dulcis Forst. syn. Spondias cytherea Sonn
Good Agricultural Practices, 73
Good Hygienic Practices, 73
Good Manufacturing Practices, 73
Graham *see Mangifera indica* L.
grape berry moths, 188
gray mould *see Botrytis cinerea*
Green Light, 327
Groff *see Litchi chinensis* Sonn.
grosse sapote *see Pouteria sapota* Jacq. H.E. Moore & Stearn
guava *see Psidium guajava* L.
guava fruit fly *see Batrocera correcta* (Bezzi)
Guiwei *see Litchi chinensis* Sonn.
Gulabi see Artocarpus heterophyllus Lam.

Haak Yip *see Litchi chinensis* Sonn.
Haden *see Mangifera indica* L.
Hansenula, 59
harvest index, 349–50
hayko, 161
Hayward *see Actinidia* spp.
heat injury, 171
heat treatments, 387–8
Heiye *see Litchi chinensis* Sonn.
hermaphroditic, 120
4-hexylresorcinol, 391
Higgins *see Mangifera indica* L.
high temperature short time (HTST) pneumatic drying, 549
Hindi *see Mangifera indica* L.
Hindy Sinnara *see Mangifera indica* L.
Hong Huai *see Litchi chinensis* Sonn.
Hongyang *see Actinidia* spp.
Hort16A *see Actinidia* spp.
hot water immersion, 532–3
hot water treatment, 230–1, 390–1
Huaizhi *see Litchi chinensis* Sonn.
hydrochloric acid (HCI), 176
hydrolysis, 456
hypobaric pressure storage, 437–8
hypobaric storage, 317

Indarbela tetraonis, 288
Indian jujube *see Ziziphus mauritiana* Lam.
indole acetic acid (IAA), 48
internal discoloration *see* brown centres
International Macadamia Quality Standard, 454
irradiation, 231–2, 317, 535–6
Irwim *see Mangifera indica* L.

jaboticaba *see Myrciaria cauliflora* (Mart.) O.Berg. [Myrtaceae]
jackfruit *see Artocarpus heterophyllus* Lam.
Jarra *see Mangifera indica* L.
Jiefanfzhong *see Eriobotrya japonica* L.

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Jintao *see Actinidia* spp.
jujube fruit shrink disease, 309
Julia *see Mangifera indica* L.

Kaimana *see Litchi chinensis* Sonn.
Kampuchea guava, 218
Kapa Benka see Artocarpus heterophyllus Lam.
Kasargod *see Mangifera indica* L.
Keitt *see Mangifera indica* L.
Kensington Pride *see Mangifera indica* L.
Kent *see Mangifera indica* L.
Keow Savoey *see Mangifera indica* L.
Kerosene *see Mangifera indica* L.
kiwifruit *see Actinidia* spp.
Kom *see Litchi chinensis* Sonn.
Kradum, 82–5, 86–7, 91
Kurukkan *see Mangifera indica* L.
Kwai May Pink *see Litchi chinensis* Sonn.
Kwai Mi *see Litchi chinensis* Sonn.

Langra *see Mangifera indica* L.
Lasiodiplodia sp., 171
Lasiodiplodia theobromae, 377
Lasiodiplodia theobromae, 99
LDPE *see* low density polyethylene
lipolysis, 455, 456
litchi *see Litchi chinensis* Sonn.
Litchi chinensis Sonn., 361–98
  constraints during long-term storage and export, 370–9
    chilling injury, 373
    foodborne pathogens, 377–9
    micro-cracking and fruit cracking, 373–4
    pericarp browning and desiccation, 370–3
  fruit composition, 365–8
    aroma volatiles, 367–8
    ascorbic acid and mineral content, 366–7
    sugars and acids, 365–6
  fruit development, maturation and composition, 363–8
    chemical index for litchi maturity, 364
    colour and phenolic components in the pericarp, 364–5
    growth, development, maturation and respiration, 363
    maturity indices and quality components, 364
  good quality litchi fruits production for postharvest export chain, 368–70
    fertiliser application for good quality fruit, 368–70
    orchard management, 370
  modified atmosphere storage, 389–95
    biocontrol agent, 391–2
    chitosan, 392–3
    Generally Regarded As Safe compounds, 391
    hot water treatment, 390–1
    1-methylcyclopropene, 393–5
  origin, botany, morphology and structure, 361–2, Plate XXVI
  packing line operation and cold chain management, 385–6
    sorting and size grading, 385
    temperature management, 385–6
  postharvest chain and packhouse treatments, 381–6
    HCl dips, 384
    metabisulphite salts, 384–5
    sulphur dioxide fumigated fruit after 21 days storage, 382
    sulphur dioxide fumigation, 381, Plate XXVII
    sulphur dioxide fumigation procedure, 383–4
    undesirable effects of sulphur dioxide fumigation, 381–3
  postharvest decay, 374–7
    microbial ecology of litchi, 374–5
    postharvest pathogens affecting litchi, 375–7
  postharvest picking, in-field sorting and transport, 379–81
    harvesting litchi, 380
  postharvest technologies developments, 386–96
    biocontrol agents, 388–9
    controlled atmosphere storage, 395–6
    gamma irradiation, 386
    heat treatments, 387–8
    postharvest dip treatments, 386–7
  processing, 396–7
    canning, 397
    drying, 396–7
    fresh-cut processing, 396
  worldwide importance, 362–3
longan *see Dimorcarpus longan* Lour.
loquat *see Eriobotrya japonica* L.
low density polyethylene, 168
low temperature conditioning (LTC), 435
lucma *see Pouteria lucuma* (Ruiz and Pav.) Kuntze
lucmo *see Pouteria lucuma* (Ruiz and Pav.) Kuntze
lucuma *see Pouteria lucuma* (Ruiz and Pav.) Kuntze

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lúcuma *see Pouteria lucuma* (Ruiz and Pav.) Kuntze
lúcumo *see Pouteria lucuma* (Ruiz and Pav.) Kuntze
Luluma mammosa see Pouteria sapota Jacq. H.E. Moore & Stearn
Luoyangqing *see Eriobotrya japonica* L.

Mabrouka *see Mangifera indica* L.
macadamia *see Macadamia* spp
Macadamia integrifolia, 450–69
Macadamia jansenii, 450
Macadamia spp, 450–69
- culinary uses, nutritional value and health benefits, 451–2
- drying effects on quality, 461–3
  - drying methods, 462–3
  - drying regimes for macadamia nut-in-shell, 463
- factory processing, 464–8
  - after-roast darkening, 467–8
  - cracking, 464–5
  - dry roasting method used by a processor, 468
  - roasting, 465–7
  - roasting regimes in air, 467
  - roasting regimes in vegetable oils, 467
- handling and physical damage, 464
- origin, botany, morphology and structure, 450–1
  - fruit morphology, Plate XXXIII
- preharvest factors affecting nut quality, 458–9
  - crop management, 458–9
  - cultivar and site, 458
  - cultivar differences for oil content in different regions of Eastern Australia, 458
  - pests and disease, 459
- pre-harvest physiology, 452–3
  - fruit growth and development, 452–3
  - mature fruit structure, 453
- quality and the on-farm postharvest chain, 460–1
  - dehuskers and macadamia quality, 460–1
  - harvest operations, 460
  - sorting and resorting, 461
- quality components and indices, 453–7
  - appearance, 455
  - importance of antioxidants, 457
  - oil content and immaturity, 454
  - quality defects, 454–5
  - rancidity and shelf life, 455–7
  - shoulder damage, Plate XXXIV
- worldwide importance and economic value, 451

Macadamia tetraphylla, 450–69
Madras *see Litchi chinensis* Sonn.
Magiferae indica, 171
malondialdehyde, 411
mamey *see Pouteria sapota* Jacq. H.E. Moore & Stearn
mamey apple *see Mammea americana* L.
mamey colorado *see Pouteria sapota* Jacq. H.E. Moore & Stearn
Mammea americana L., 474–80
- culinary uses, nutritional value and health benefits, 475–7
- fruit development and postharvest physiology
  - growth, development and maturation, 477
  - respiration, ethylene production and ripening, 477
- insect pests, 478
- maturity and quality components and indices, 477
- nutrient value per 100 g of fruit, 476
- origin, botany, morphology and structure, 474–5
  - tree and fruit, Plate XXXV
- pathological disorders, 478
- physiological disorders, 478
- postharvest handling factors affecting quality
  - atmosphere, 478
  - temperature management, 478
- postharvest handling practices, 478–9
  - harvest operations, 478
  - recommended storage and shipping, 479
  - ripening and senescence control, 479
- processing, 479
- worldwide importance, 475

mammee apple *see Mammea americana* L.
mammein, 477
mammey sapote *see Pouteria sapota* Jacq. H.E. Moore & Stearn
mammon *see Pouteria lucuma* (Ruiz and Pav.) Kuntze
Mancozeb, 5
Mangifera indica L., 492–550
- botany, morphology and structure, 494
- chemicals effect on quality, 514–15
  - growth regulators, 515
  - pests and disease control, 514–15
- composition of edible portion, 498–9

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control of pathological diseases, 526–8
biological control, 526–7
chemical treatments, 527
heat treatments, 527–8
irradiation, 528
external and internal colour changes during maturation and ripening, Plate XXXIX
fruit development and postharvest physiology, 501–9
compositional changes during fruit maturation and ripening, 504–8
growth, development and maturation, 501
manipulation of postharvest physiology by molecular biology, 508–9
respiration, ethylene production and ripening, 501–4
insect pests, 528–31
fruit flies, 529–30
mango weevils, 530–1
insect quarantine treatments, 531–6
chemical control, 531–2
heat treatments, 532–4
irradiation, 535–6
modified and controlled atmospheres, 534–5
'Manila' fruit, 495
maturity and quality components and indices, 509–12
use of computation in different ASEAN countries, 511
nutritional value and health benefits, 497–501
pathological diseases, 524–6
Alternaria rot, 526
Anthracnose, 525
Aspergillus rot, 526
other diseases, 526
stem-end rot, 525
physiological disorders, 521–4
biennial bearing, 521
chilling injury, 523
internal breakdown, 522
other physiological disorders, 523–4
postharvest handling factors affecting quality, 515–21
atmosphere, 516–21
physical damage, 515–16
temperature management, 515
transpiration and water loss, 516
postharvest handling practices, 536–44
clamshell for six 'Ataulfo' mangoes, 543
harvesting and collection of mango, 536
harvest operations, 536–9
latex exudates on mango fruit, 537
mango package, 542
mango packinghouse, Plate XL
packinghouse practices, 539–43
recommended storage and shipping conditions, 544
ripening and its control, 543
washing of mango fruit in packinghouse, 540
waxing, 540–1
preharvest factors affecting fruit quality, 513–15
bagging, 515
fertilisation, 514
light, 513
rainfall and irrigation, 514
temperature, 513–14
processing, 544–9
fresh-cut, 544–7
other processing practices, 548–9
'Tommy Atkins' external and internal colour changes, Plate XXXVIII
tree and fruit, 493
worldwide importance and economic value, 494–7
mango *see Mangifera indica* L.
mango juice, 548–9
mango nectar, 548–9
mango squash, 549
mango weevil *see Cryptorhynchus mangiferae*
Manila *see Mangifera indica* L.
marco *see Pouteria lucuma* (Ruiz and Pav.) Kuntze
Margaronia caecalis, 288
marmalade-fruit *see Pouteria sapota* Jacq. H.E. Moore & Stearn
marmalade-plum *see Pouteria sapota* Jacq. H.E. Moore & Stearn
mature coconut
maturity indices, 17
physiological disorders and pests, 20–1
disease, 20–1
growth, 21
insect damage, 21
rodent damage, 21
postharvest handling factors affecting quality, 18–20
atmosphere, 20
humidity, 19

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physical damage, 18
temperature, 19
postharvest handling practices, 21–6
harvest operations, 22
packing house practices, 24
recommended storage and shipping conditions, 26
ripening and senescence control, 25
quality components, 12–15
moisture, sugar, acid and oil content, 13–14
other components, 14–15
mature-green stage, 493
Mauritius *see Litchi chinensis* Sonn.
Mazagaon *see Mangifera indica* L.
McLean's Red *see Litchi chinensis* Sonn.
mealybugs, 188
Mediterranean fruit fly *see Ceratitis capitata* (Wiedemann)
methyl bromide, 62, 201
methyl bromide (MeBr), 531–2
1-methylcyclopropene, 127, 305–6, 393–5
Mexican fruit fly *see Anastrepha ludens* Loew
Misk *see Mangifera indica* L.
modified atmosphere packaging, 224–5, 389–95, 435–6
Mogi *see Eriobotrya japonica* L.
Monthong durian, 82–5, 91
antioxidant capacity and penolic contents, 83
cross section, Plate IX
dry matter content, 90
firmness and uneven ripening score harvested from trees, 98
morphactin, 229
Mudaria magniplaga Walker, 100
Muttam Varikha see Artocarpus heterophyllus Lam.
Myrciaria cauliflora (Mart.) O.Berg. [Myrtaceae], 246–70
culinary uses, nutritional value and health benefits, 252–4
chemical composition, 253
common phenolics, 254
fruit development and postharvest physiology, 254–6
growth, development and maturation, 254–5
pigment content, 255
respiration, ethylene production and ripening, 255–6
insect pests, 265–6
important pests, 265
maturity and quality components and indices, 256–60
anthocyanin content, 260
changes in organic acids after flowering, 258
non-structural carbohydrates content, 257
structural carbohydrates content, 259
origin, botany, morphology and structure, 246–51
Brazilian centres of diversity for native fruits, 247
development into fruits and flowers, Plate XX
dry matter accumulation and volume change, 250
genetic similarity pattern, 249
main species, common names and origins, 248
morphological aspects, 251
pathological disorders, 264–5
important diseases, 264
physiological disorders, 264
postharvest handling factors affecting quality, 261–4
atmosphere, 263–4
physical damage, 262
temperature management, 261–2
water loss, 262–3
postharvest handling practices, 266–8
harvest operations, 266
packinghouse practices, 267
recommended storage and shipping conditions, 267–8
preharvest factors affecting fruit quality, 260–1
processing, 268–70
fresh-cut processing, 268
jelly, 269–70
liqueur, 268–9
phenolics, tannins, anthocyanins and antioxidants, 269
total acidity, volatile acidity, alcohol content, pH, 270
vinegar, 270
wine, 269
worldwide importance and economic value, 251–2
Myrciaria tenella, 250
Myrciaria trunciflora, 250

Namdokami *see Mangifera indica* L.
Nam Dok Mai *see Mangifera indica* L.
Nang Klang Wun *see Mangifera indica* L.

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nata de coco, 29
Necrobia rufipes de Geer., 21
Neoleucenoides elegantalis, 5
Nileswar Dwarf *see Mangifera indica* L.
nitric oxide, 306
NOM-FF–58–1985, 512
non-enzymatic (Maillard) browning, 130
Numici *see Litchi chinensis* Sonn.
Nuomici *see Litchi chinensis* Sonn.
nuts, 418

oil roasting, 466
Olour *see Mangifera indica* L.
organoleptic tests, 162
Oro *see Mangifera indica* L.
oxalic acid/ammonium oxalate (OAAO), 176

Paho *see Mangifera indica* L.
Pairi *see Mangifera indica* L.
PAL enzyme, 394
Palmer *see Mangifera indica* L.
Palo *see Pouteria lucuma* (Ruiz and Pav.) Kuntze
palo negro *see* waterberry
Parrot *see Mangifera indica* L.
pasteurisation, 68
Peach/Apricot *see Mangifera indica* L.
peach tomato *see Solanum sessiliflorum* Dunal
pectin, 176
Pectinex Ultra SP-L, 176
Pelliculana salmonicolor, 288
Penconazol, 5
Penicillium expansum, 186–7
Penicillum spp, 375–6, 388
perforated MA, 520
Peronophythora litchi, 377
peroxidase (POD), 371–2
Phoenix dactylifera L., 41–74
  Barhee dates, Plate VI
  control methods, 61–3
    biological control, 63
    fumigation, 62
    high temperatures, 61
    ionising radiation, 62
    low temperatures, 61–2
    modified atmospheres and controlled atmospheres, 63
  dates market in Saudi Arabia, 42
  factors affecting fruit development and ripening, 46–7
    mineral nutrition, 47
    relative humidity and rainfall, 46–7
    temperature, 46
  food safety considerations, 72–3
  fruit growth and development, 45–50
    biochemical changes, 48–50
    fruit set, 45–6
    fruit thinning, 46
    growth pattern, 47
    growth regulators, 47–8
    pollination, 45
  harvesting, 63–6
    illustration, 65
    removing defective dates from strands, 65
    roadside selling in southern Tunisia, 64
  insect pests, 60–1
  maturity and harvesting indices, 53–4
  nutritional components and health benefits, 50–2
  pathological disorders, 59–60
    disease control strategies, 60
    fungi, 59–60
    souring, 59
  physiological disorders, 57–9
    black nose, 58
    darkening, 57
    internal breakdown, 58
    mixed green, 59
    skin separation (puffiness), 57–8
    splitting, 59
    sugar spotting (sugaring), 58
    white nose, 58–9
  postharvest handling factors affecting quality, 57
  postharvest handling practices, 63–72
    dehydration, 67
    handling organic dates, 71–2
    hydration, 67–8
    pasteurisation, 68
    ripening, 66–7
    storage condition, 70–1
  postharvest physiology, 52–3
    ethylene production and responses, 52
    respiration, 52
    responses to modified and controlled atmospheres, 53
  preharvest factors affecting postharvest fruit quality, 56–7
  preparation for market, 68–70
    cleaning, 68
    cooling, 69–70
    ‘Deglet Noor’ dates consumer packages, 70
    packaged dates, 69

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packaging, 69
sizing, 68–9
sorting, 68
surface coating, 69
processing, 72
production in some important producing countries (2007), 42
quality indices, 54–6
characteristics and criteria, 54–5
protective covers for date bunches, 55
standard grades, 55–6
US standard, 56
removing defective dates from bunches, Plate VII
Tamar stage of 'Deglet Noor' dates, 44
Phomopsis artocarpina, 288
phosphine, 62
Phyrdenus muriceus Germar, 5
Phytophthora fruit rot, 228
Phytophthora infestans, 5
Phytophthora palmivola, 432
Phytopthora palmivora Butler, 98, 99
Pichia anomala Moh93, 229
Pichia anomala Moh104, 229
pickles, 548
Pico *see Mangifera indica* L.
Pierie *see Mangifera indica* L.
Planococcus pacificus Cox, 5
polgalacturonase (PG), 86
pollination, 45
polyethylene plastic bag, 38–9
polyphenolic compounds, 429–30
polyphenol oxidase (PPO), 371–2, 391, 429–30
polyphenol oxydase (PPO), 128–9
postharvest dip treatments, 386–7
potash, 514
potassium fertiliser, 17
Pouteria lucuma (Ruiz and Pav.) Kuntze, 443–8
classification on basis of peel and pulp colour, 446
culinary uses, nutritional value and health benefits, 444–5
fruit development and postharvest physiology
growth, development and maturation, 445
respiration, ethylene production and ripening, 445
insect pests and their control, 447
maturity and quality components and indices, 446
nutritional value per 100 g of fruit, 445
origin, botany, morphology and structure, 443–4
fruit structure, Plate XXXII
physiological disorders, 446
postharvest handling factors affecting quality
physical damage, 446
temperature management, 446
water loss, 446
postharvest handling practices
harvest operations, 447
recommended storage and shipping conditions, 447
ripening and senescence control, 447
processing, 447–8
worldwide importance, 444
Pouteria sapota Jacq. H.E. Moore & Stearn, 482–9
chilling injury, 486
culinary uses, nutritional value and health benefits, 483–4
fruit sold in Mexico, Plate XXXVII
mamey sapote fruit, Plate XXXVI
insect pests and their control, 487
maturity and quality components and indices, 485
nutrient value per 100 g of fruit, 484
origin, botany, morphology and structure, 482–3
pathological disorders, 486–7
physiological disorders, 486
postharvest handling factors affecting quality, 485–6
temperature management, 485–6
water loss, 486
postharvest handling practices, 487–8
harvest operations, 487
packinghouse practices, 487
recommended storage and shipping conditions, 488
ripening and senescence control, 488
ripening rates in fruits after ethylene treatments, 488
postharvest physiology, 484–5
processing, 488–9
worldwide importance, 483
pozol, 484
preharvest bagging, 221
Prochloraz, 388
prochloraz, 229
"Pro-long" semipermeable fruit coating, 521
Pseudomonas solanacearum, 5
Pseudomonas syringae, 432

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Psidium guajava L., 213–39
  maturity indices, 219–20
  origin, botany, morphology and structure, 213–14
    guava fruit and leaves, 214
    salmon to pink-fleshed guava fruit, Plate XIX
    white-fleshed guava fruit, Plate XVIII
  physiological disorders, 227–8
  postharvest handling factors affecting fruit quality, 222–7
    physical damage, 223–4
    temperature management, 222–3
  postharvest handling practices, 232–5
    harvest operations, 232
    packinghouse practices, 233–4
    recommended storage and shipping, 235
    ripening and senescence control, 234–5
  postharvest insect-pests and phytosanitary treatments, 230–2
    heat and cold treatments, 230–1
    irradiation, 231–2
  postharvest pathological disorders, 228–30
  postharvest physiology, 216–19
    biochemical changes during fruit ripening, 218–19
    fruit growth, development and maturation, 216–17
    respiration and ethylene production, 217–18
  preharvest factors affecting fruit quality, 220–2
    canopy position and tree age, 221–2
    fruiting season, 220
    mineral nutrients, growth regulators and other chemicals, 222
    orchard practices, 221
  processing, 235–8
    fresh-cut, 235–6
    other processed products, 237–8
  storage atmosphere, 225–7
    controlled atmosphere, 226–7
    short-term modified atmosphere exposure, 225–6
  uses, nutritional value and health benefits, 215–16
  water loss, 224–5
    modified atmosphere packaging, 224–5
    surface coatings, 225
  worldwide distribution and economic importance, 214–15
    major cultivars, 215

Puccinia psidii Wint., 264
purple spot, 430–1
putrescine, 429
Pythium, 5

quarantine treatment, 129
quercetin, 87

Rad *see Mangifera indica* L.
rancidity, 455–6
Raspuri *see Mangifera indica* L.
Rataul *see Mangifera indica* L.
reddish-brown beetle *see Tribolium castaneu* Herbst
relative humidity, 95
Rhizoctonia, 5
Rhizopus, 526
Rhizopus artocarpi, 288
Rhizopus nigricans Ehr, 60
Rhizopus rot, 187
Rhizopus sp., 21
ripe fruit mealy bug *see Planococcus pacificus* Cox
ripe rots, 345
root-knot nematodes, 150
rots, 344
rucma *see Pouteria lucuma* (Ruiz and Pav.) Kuntze

Sabre *see Mangifera indica* L.
Saigon *see Mangifera indica* L.
Salem *see Mangifera indica* L.
Sammar Bahisht *see Mangifera indica* L.
Sammini *see Mangifera indica* L.
sanitation standard operating procedures, 73
sapote *see Pouteria sapota* Jacq. H.E. Moore & Stearn
sapote mamey *see Pouteria sapota* Jacq. H.E. Moore & Stearn
Seda *see Pouteria lucuma* (Ruiz and Pav.) Kuntze
Sensation *see Mangifera indica* L.
Septoria solanicola, 5
shanking *see* waterberry
sheet pitting, 169
Shixia *see Dimorcarpus longan* Lour.
short-term modified atmosphere, 224–5
shoulder damage, 455
Simmonds *see Mangifera indica* L.
Singapore Jack see Artocarpus heterophyllus Lam.
SmartFresh, 334
SMS solution, 25

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smut, 148
Solanum sessiliflorum Dunal, 1–6
 composition, 3
 culinary uses, nutritional value and health benefits, 3
 fruit development and postharvest physiology, 3–4
  growth, development and maturation, 3–4
  respiration and ethylene production and ripening, 4
 insect-pests and their control, 5
 maturity and quality components and indices, 4
 origin, botany, morphology and structure, 1–2
  fruit, Plate II
  plants showing immature and mature fruits, Plate I
 pathological disorders, 5
 physiological disorders, 4–5
 postharvest factors affecting quality, 4
 postharvest handling practices, 6
 preharvest factors affecting quality, 4
 processing, 6
 worldwide importance and economic value, 2
soluble solids concentration, 140
Souey Tung *see Litchi chinensis* Sonn.
souring, 148
South America apricot *see Mammea americana* L.
spermidine, 429
spermine, 429
Spondias dulcis Forst. syn. *Spondias cytherea* Sonn, 159–77
 culinary uses, nutritional value and health benefits, 161–2
 fruit development and postharvest physiology, 162–5
  changes during growth and development, 163
  compositional changes, 164
  ethylene production at three stages of fruit maturity during storage, 165
  growth, development and maturation, 162
  respiration and ethylene production and ripening, 162–5
 insect pests and control, 172–3
  mature green and ripe fruits, Plate XV
 maturity indices and quality components, 165–6
 origin, botany, morphology and structure, 159–60
  miniature and large types, Plate XIV
 packaging and waxing effect
  bioelectrical resistance, 169
  electrolyte leakage, 170
  percentage marketable and decayed fruits, 168
 pathological disorders, 171–2
 physiological disorders, 169–71
  chilling injury, 169–71
  heat treatments effect on selected quality attributes, 170
  other physiological disorders, 171
 postharvest handling factors affecting quality, 166–9
  atmosphere, 168
  physical damage, 167
  temperature management, 166–7
  water loss, 167–8
 postharvest handling practices, 173–5
  harvest operations, 173
  packinghouse practices, 173–4
  recommended storage and shipping conditions, 174–5
  ripening and senescence control, 174
 preharvest factors affecting fruit quality, 166
 processing, 175–6
  fresh-cut processing, 175
  other processing options, 175–6
 worldwide importance and economic value, 160–1
spray-dried mango powders, 549
SSC *see* soluble solids concentration
stationary lag stage, 183
St Domingo apricot *see Mammea americana* L.
stem-end rot, 344–5, 525
stiellahme see waterberry
Strawberry *see Mangifera indica* L.
stylar end rot, 228
Sukkary *see Mangifera indica* L.
sulphur dioxide, 130
 fumigation, 149, 381–4
 generator pads, 198–9
 treatments, 196–201
  alternatives, 200–1
  dosages, 197
  effect of temperature on toxicity, 197
  evolution of concentration from generating pad, 199
  evolution of gas obtained with generating pad, 200

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mode of action, 196–7
post-packaging fumigation, 198–200
pre-packaging fumigation, 198
tolerance, 200
Summerkiwi, 327
sunbathe, 37
sun drying, 549
superoxide dismutase, 411
Suvamarekha *see Mangifera indica* L.
syconium, 137

TA *see* titratable acidity
table grapes *see Vitis vinifera* L.
Taimour *see Mangifera indica* L.
Tai So *see Litchi chinensis* Sonn.
Tanaka *see Eriobotrya japonica* L.
terpinolene, 538
thick liquid disease, 309–10
titratable acidity, 140
Tommy Atkins *see Mangifera indica* L.
Tongbi *see Dimorcarpus longan* Lour.
Tongdum *see Mangifera indica* L.
Top Star, 327
total titratable acidity, 162
Totapuri *see* Mangifera indica L.
touch picking, 122, 124
Toxoptera aurantii, 266
Tribolium castaneu Herbst, 21
Trigonas spinipes, 266
Tuzhong *see Dimorcarpus longan* Lour.

ultra high temperature (UHT), 28
ultraviolet light-C, 236
UN/ECE standard FFV–45, 513
United States Environmental Protection Agency (USEPA), 62
unsound kernel, 454, 458

Vapogard, 387
vapour heat treatment, 231, 533–4
vibration method, 92
vinegar flies, 188
Vitellaria mammosa see Pouteria sapota Jacq. H.E. Moore & Stearn
Vitis vinifera L., 179–207
abiotic agents, 188–92
berry splitting and hairline cracks, 190
bleaching, 188
bleaching symptoms, Plate XVI
browning symptoms, Plate XVII
dehydration, 188–9
hairline cracks, 189
shatter, 189–90
skin and flesh browning, 190–1
splitting, 191
waterberry, 191–2
biotic factors, 185–8
Aspergillus rot, 187
blue mould, 186–7
Cladosporium rot, 187
gray mould, 185–6
gray mould symptoms, 186
insect damage, 188
other decay fungi, 187–8
Rhizopus rot, 187
cultivars, 180
maximum storage time, deterioration factors and origin, 180
deterioration factors, 184–92
fruit anatomy, 181–2
cluster and berry components, 181
physiology of berry growth and maturation, 182–4
development, accumulation of soluble solid and titratable acidity of “Thompson Seedless,” 182
respiration heat, 184
postharvest handling and packaging, 192–6
cooling operation, 194–6
forced air cooling, 195
harvest operation, 192
labelling, 193
packaging operation, 192–3
pallets with two box arrangement types, 194
working table in packing line operation, 193
processing, 204–7
quarantine treatments, 201
methyl bromide fumigation, 201
raisins, 204–7
dried-on-vine, 206
grape cultivars and type of raisins, 204–5
grape drying, 205
grape harvesting, 205
hot-air drying, 206
processing, 206–7
production process, 205
sun-dried, 205
sulphur dioxide treatments, 196–201
alternatives, 200–1
dosages, 197
effect of temperature on toxicity, 197
evolution of concentration from generating pad, 199

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evolution of SO_2 gas obtained with generating pad, 200
mode of action, 196–7
post-packaging fumigation, 198–200
pre-packaging fumigation, 198
tolerance, 200
temperature management, 196
transport, 202–3
dewpoint temperature, 203
marine containers, 202–3
pallet distribution inside container, 203

Wai Chee *see Litchi chinensis* Sonn.
water activity, 461
waterberry, 191–2
water soaked core *see* wet core
waxing, 168
wet core, 96
white nose, 58–9
wind damage, 128
Wuxing *see Eriobotrya japonica* L.

Xanthomonas campestris pv., 171
xenia effect, 17
Xtend, 389, 390

yellow jackets, 188
young coconut
maturity indices, 15–17
trimmed young coconut fruit, 16
physiological disorders and pests, 20
postharvest handling factors affecting quality, 18–20
atmosphere, 19–20
humidity, 19
physical damage, 18
temperature, 18–19
postharvest handling practices, 21–5
harvest operations, 21–2
packing house practices, 22–4
recommended storage and shipping conditions, 25
ripening and senescence control, 24–5
quality components
moisture, sugar, acid and oil content, 13

Zaozhong 6 *see Eriobotrya japonica* L.
zapote *see Pouteria sapota* Jacq. H.E. Moore & Stearn
Zebda *see Mangifera indica* L.
ZESPRI, 327
Zill *see Mangifera indica* L.
Ziziphus jujuba Mill., 299–321
nutritional value and health benefits, 300–3
Dongzao jujube grading standard, 303
nutrition content, 301–2
red jujube grading standard, 303
origin, botany and morphology, 299–300
varieties, Plate XXIII
postharvest disorders, 311
postharvest handling, 318–19
grading, 318
packaging, 318–19
storage at ambient temperature, 318
postharvest pathology, 307–10
diseases, 308–9
foot rot of fruit stem, 310
jujube fruit shrink disease, 309
thick liquid disease, 309–10
postharvest pathology and entomology, 307–11
postharvest entomology, 311
postharvest pathology control, 310–11
biological control, 310–11
physical and chemical control, 310
postharvest treatments to extend shelf-life, 313–18
calcium solution treatment, 316
chlorine dioxide treatment, 316
controlled atmosphere, 314–15
ethanol treatment, 317
heat treatment, 317–18
hypobaric storage, 317
irradiation, 317
low-temperature storage, 313–14
other treatments, 318
ozone application, 315
preservative treatments, 316
preharvest treatments to extend shelf life, 312–13
bagging, 313
calcium treatment, 312–13
varieties and harvest maturity, 312
processing, 319–21
candied jujube, 320
dehydrated jujube products, 319
frozen jujube fruit, 321
jujube juice and beverages, 320–1
processed Chinese jujube, 320
ripening behaviour and postharvest physiology, 304–7
artificial ripening, 307
ethylene and carbon dioxide evolution rates, 304–5
ripening behaviour, 304
treatments to reduce respiration and ethylene rates, 305–6
calcium, 306

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gibberellic acid, 306
low pressure, 305
low temperature, 305
1-methylcyclopropene, 305–6
nitric oxide, 306
Ziziphus mauritiana Lam., 299–321
nutritional value and health benefits, 300–3
Dongzao jujube grading standard, 303
nutrition content, 301–2
red jujube grading standard, 303
origin, botany and morphology, 299–300
postharvest disorders, 311
postharvest handling, 318–19
grading, 318
packaging, 318–19
storage at ambient temperature, 318
postharvest pathology, 307–10
diseases, 308–9
foot rot of fruit stem, 310
jujube fruit shrink disease, 309
thick liquid disease, 309–10
postharvest pathology and entomology, 307–11
postharvest entomology, 311
postharvest pathology control, 310–11
biological control, 310–11
physical and chemical control, 310
postharvest treatments to extend shelf-life, 313–18
calcium solution treatment, 316
chlorine dioxide treatment, 316
controlled atmosphere, 314–15
ethanol treatment, 317
heat treatment, 317–18
hypobaric storage, 317
irradiation, 317
low-temperature storage, 313–14
other treatments, 318
ozone application, 315
preservative treatments, 316
preharvest treatments to extend shelf life, 312–13
bagging, 313
calcium treatment, 312–13
varieties and harvest maturity, 312
processing, 319–21
candied jujube, 320
dehydrated jujube products, 319
frozen jujube fruit, 321
jujube juice and beverages, 320–1
ripening behaviour and postharvest physiology, 304–7
artificial ripening, 307
ethylene and carbon dioxide evolution rates, 304–5
ripening behaviour, 304
treatments to reduce respiration and ethylene rates, 305–6
calcium, 306
gibberellic acid, 306
low pressure, 305
low temperature, 305
1-methylcyclopropene, 305–6
nitric oxide, 306
Zygosaccharomyces, 59

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