POSTHARVEST

An Introduction to the Physiology and Handling of Fruit and Vegetables

6TH EDITION

RON WILLS AND JOHN GOLDING

CABI

POSTHARVEST

6TH EDITION

DR RON B.H. WILLS is an Emeritus Professor in the School of Environmental and Life Sciences at the University of Newcastle, Australia. He has more than 40 years' experience in postharvest horticulture and has published close to 300 research papers. He has held government, university and industry positions in Australia and New Zealand and has consulted widely throughout Asia.

DR JOHN B. GOLDING works with the postharvest/market access team in the New South Wales Department of Primary Industries, Australia. He works on the market access and quality along the supply chain of a range of fruit and vegetable crops for the domestic and overseas markets. John has over 25 years' experience in postharvest horticulture, and is a conjoint lecturer at the University of Newcastle.

This page intentionally left blank

POSTHARVEST

AN INTRODUCTION TO THE PHYSIOLOGY AND HANDLING OF FRUIT AND VEGETABLES

6TH EDITION

RON B.H. WILLS • JOHN B. GOLDING

UNSW PRESS

CABI

Published in Australia and New Zealand by
UNSW Press
an imprint of NewSouth Publishing
University of New South Wales Press Ltd
University of New South Wales
Sydney NSW 2052 AUSTRALIA
newsouthpublishing.com

Published in the rest of the world by
CABI, a trading name of CAB International

CABI
Nosworthy Way
Wallingford
Oxfordshire OX10 8DE UK

Tel: +44 (0)1491 832111
E-mail: info@cabi.org
Website: www.cabi.org

CABI
745 Atlantic Avenue
8th Floor
Boston, MA 02111 USA

Tel: +1 (617)682 9015
E-mail: cabi-nao@cabi.org

First published 1981. Second revised edition 1982. Third revised edition 1989.
Fourth revised edition 1998. Fifth revised edition 2007.

ISBN: 9781742234878 (UNSW Press)
9781786391483 (CABI)

10 9 8 7 6 5 4 3 2 1

National Library of Australia Cataloguing-in-Publication entry
Creator: Wills, R. B. H. (Ronald Baden Howe) author.
Title: Postharvest: an introduction to the physiology and handling of fruit and vegetables / Ron Wills, John Golding.
Edition: 6th edition
ISBN: 9781742234878 (paperback)
9781742247854 (ePDF)
Notes: Includes index.
Subjects: Vegetables – Postharvest physiology. Vegetables – Postharvest technology. Vegetables – Marketing. Vegetables – Storage. Fruit – Postharvest physiology. Fruit – Postharvest technology. Fruit – Marketing. Fruit – Storage. Agricultural processing.
Other Creators/Contributors: Golding, John, author.
Dewey Number: 635.046

A catalogue record for this book is available from the British Library, London, UK.

Design Josephine Pajor-Markus
Cover image Mandarins at Abbotsleigh Citrus, Queensland. Photo: Clare De Luca, Fresh Republic.
Printer Everbest, China

Contents

Preface

Postharvest technology and the marketing of fruit and vegetables have changed markedly since *Postharvest* was first published in 1981. The growth in international trade and its counter-seasonal effect has resulted in many types of produce being available for 12 months of the year. There is now a greater variety of horticultural produce available in most countries, which has given consumers a wider range of safe and nutritious fruit and vegetables with diverse flavours and uses. Tropical countries in particular have benefited from being able to market in distant temperate countries.

In 1981, postharvest technology was only emerging as a distinct scientific discipline to support a more efficient handling of horticultural produce from the farm gate to the consumer. Over the years it has matured into a vibrant research community that works closely with fruit and vegetable industries and supply chains to provide integrated and cost-effective systems and technologies to meet market requirements. Academic institutions have responded to the growing importance of fruit and vegetables as a food and trading commodity by establishing specialist postharvest training courses. The spread of postharvest as a science has been greatest in developing countries, with governments actively supporting the training of postharvest professionals and establishing national research and extension organisations.

In the 1981 edition, one of the stated objectives of postharvest technology was to reduce the considerable losses that existed throughout the postharvest chain. While this is still important in 2016, it has been complemented by concerns about a range of quality, food safety and management issues. Indeed there has been considerable change in consumer and industry attitudes since publication of the 5th edition in 2007, with the greatest influence being the rise of consumer power. The electronic information age has been a powerful force in the rapid spread of new concepts in all fields. This has affected the fruit and vegetable industry, raising questions on what are desirable quality attributes and how the industry can achieve these attributes. A major influence has been interest in global sustainability, which looks at how industry practices are impacting on the environment, particularly in terms of greenhouse gas emissions through reducing energy usage and whether more healthy fruit and vegetables can be marketed. This edition addresses the changing expectations for fruit and vegetable quality and practices and how researchers and producers are responding with technologies that meet the new consumer expectations.

The book begins with updated information on the basic tenets of postharvest technology, which are the structure of fruit and vegetables and how this influences their postharvest behaviour, then summarises key information about their composition, biochemistry, respiration and physiology. Temperature and humidity control are the core technologies for maintaining fresh quality, and their management is discussed in depth. Fresh produce is also susceptible to various pathogenic diseases and physiological disorders that need to be identified and controlled by environmentally friendly methods. Technologies that are adjuncts to temperature management, including atmosphere control, controlled ripening, packaging and transport, are discussed in some detail. Also outlined are the principles underlying the food safety based quality assurance systems that also meet environmental requirements. The final chapter examines how consumers are influencing the marketing and storage of fruit and vegetables.

This text is an introductory primer for tertiary courses and for people working along the supply chain from farm or orchard to the retail store or food service providers. It will also be a useful resource for discerning consumers.

Acknowledgments

The current edition was generated by building upon the successful platform created by the authors of the past five editions: Terry Lee, Barry McGlasson, Doug Graham, Eric Hall and Daryl Joyce. We wish to thank the past authors and all other contributors for the evolution of postharvest knowledge in *Postharvest* and to specifically thank Dr Len Tesoriero and Dr SP Singh (NSW Department of Primary Industries) for their assistance with this edition.

1
Introduction

Importance of fruit and vegetables as food

Fresh fruit and vegetables have been part of the human diet since hunter-gatherer times, but many societies have tended to value foods from animal sources more highly. Nevertheless, substantial numbers of people have diets that are largely or totally vegetarian and hence greatly depend on fruit and vegetables. The perceived value of fruit and vegetables in the diet has risen considerably in recent years, and health professionals are recommending increased consumption of fruit and vegetables often in association with restricted consumption of animal foods. The World Health Organization (WHO) recommends consumption of a minimum of 400 g of fruit and vegetables per day (excluding starchy root crops) for the prevention of chronic diseases associated with a sedentary lifestyle common in developed urban societies and of various micronutrient deficiencies mainly in less developed countries. Fruit and vegetables are one of the five food groups used by nutritionists to promote a healthy diet, and a common recommendation is for at least seven servings of fruit and vegetables to be consumed every day.

Despite the absence of modern science, the nutritional value of some fruit and vegetables was recognised in earlier times. For example, the ability of citrus fruit to cure the disease scurvy, which was widespread among naval personnel, was known in early seventeenth century England. While individual captains took advantage of this knowledge to maintain the health of crews on long voyages, it was not until the late eighteenth century that the Royal Navy issued a regular ration of lime juice to all sailors, leading to the application of the term 'limeys' to British sailors. The discovery of ascorbic acid (vitamin C) as the ingredient responsible for the wound healing properties that also prevent scurvy did not occur until the 1930s. Dietary sources of vitamin C are essential, as humans lack the ability to synthesise it. All fruit and vegetables contain vitamin C and as a group it is the major dietary source, supplying about 95% of body requirements.

Specific fruit and vegetables are also excellent sources of the other nutrients required for human health. For example, provitamin A carotenoids which are essential for maintenance of ocular health, and folic acid which prevents certain anaemias and spinal defects during foetal development. The Food and Agriculture Organization of the United Nations (FAO) and WHO have had active programs over many years promoting the use of home vegetable gardens as an inexpensive, readily available approach to combat vitamin deficiency diseases in many regions.

The recognition of the nutritional importance of fruit and vegetables has been stimulated by a range of degenerative diseases prevalent in sedentary affluent societies, particularly in Western countries. Epidemiological evidence shows that communities consuming higher amounts of fruit and vegetables have lower incidences of such diseases. Dietary fibre is now accepted as important in reducing or preventing a raft of adverse medical conditions related to its interactions with the gastrointestinal tract. Some advantages of consuming fibre are the production of healthful compounds during the fermentation of soluble fibre, and the ability of insoluble fibre to increase soft stool bulk and shorten transit time through the intestinal tract. Fruit and vegetables are considered a good source of dietary fibre and are thus promoted as a counter to highly refined plant-based foods.

In recent years, there has been considerable interest in the potential health benefits from various antioxidants in fruit and vegetables. Vitamins such as C, E and provitamin A, other carotenoids such as lycopene and lutein, and polyphenols such as anthocyanins and tannins have antioxidant properties. It has been speculated that the action of such antioxidants can prevent cancer and coronary heart disease. The notion of 'superfoods' has been used, mainly as a marketing tool for plants considered to have high antioxidant properties. However, a considerable number of clinical trials of isolated antioxidants have to date not generated conclusive support for such health benefits, and the amounts needed to exert some effects often exceed common dietary doses; but adherents have speculated that dietary antioxidants may act differently to isolated supplements.

The status of fresh fruit and vegetables has also benefited from an international trend towards fresh natural foods, which are perceived to be superior to processed foods and contain less chemical additives. This community perception has placed additional pressures on the horticultural industry to retain its fresh natural image by minimising the use of synthetic chemicals during production and postharvest handling. Notwithstanding the nutritional status and fresh natural appeal, the attraction of fruit and vegetables for many consumers is their unique sensory appeal. Fruit and vegetables provide variety in the diet through differences in colour, shape, taste, aroma and texture that distinguish them from the other major food groups of grain, meat and dairy products and for the diversity of these attributes between individual items of produce. The sensory appeal of fruit and vegetables is not confined to consumption but also has market value. The colour and shape diversity is used to great effect by traders in product displays to attract potential purchasers, and chefs have traditionally used fruit and vegetables to enhance the attractiveness of prepared dishes or table presentations. Parsley and similar herbs are widely used to adorn meat displays throughout the Western world, while fruit and vegetable carvings as table ornaments have become an art form in countries such as Thailand.

Horticultural production statistics

Production of fruit and vegetables worldwide has been increasing over many years, partly in response to a rising world population but also due to rising living standards in many countries and government health promotion of fruit and vegetable consumption. FAO data indicates the total world production of fruit and vegetables increased by 150% in the 20-year period from 1990–2010. Over the last decade, production has been growing at about 3% per annum and in 2011 it was 640 million tonnes of fruit and 1 billion tonnes of vegetables. Table 1.1 shows that China is responsible for the bulk of this increase. China has produced a four-fold increase in production over this period and accounts for 40% of world fruit and vegetable production. The second largest producer is India, which now accounts for about 10% of world production and has achieved a similar proportional increase to China. Most of the growth in production from elsewhere has also come from developing countries, with some substantial increases from countries such as Bangladesh, which has increased production by 10% in the last 10 years, to about 8 million tonnes. There have actually been small decreases in output from traditional producers such as the USA, Italy and Spain; while France and Japan are no longer in the top 10 producers, with production declining in each country from 21 million tonnes to 14 million tonnes over the same 20-year period.

Table 1.1 Major national producers of fruit and vegetables from 1990 to 2010

Country	Production (million tonnes)			Per cent of 2010 world production
	1990	2000	2010	
China	150	388	662	40
India	76	119	176	11
USA	56	68	62	4
Brazil	36	43	50	3
Turkey	27	35	40	3
Iran	15	24	32	2
Italy	32	34	31	2
Egypt	13	21	29	2
Mexico	16	23	28	2
Spain	24	28	27	2

SOURCE FAO Statistical Yearbook 2013.World food and agriculture. FAO, Rome, 2013 ◂www.fao.org/docrep/018/i3107e/i3107e00.htm▸.

FAO statistics for fruit and vegetables do not include root crops, which are listed separately due to being classed as staples in the diet in many sub-Saharan African, Latin American and Caribbean countries. The world production of root crops

Table 1.2 Major international traders in fruit and vegetables in 2010 (per cent of total world value)

Country	Export	Country	Import
EU	37	EU	47
USA	11	USA	13
China	7	China	3
Mexico	5	Russia	2
Turkey	4	Canada	2
Chile	3	Mexico	1
Canada	3		
Iran	2		
South Africa	2		

SOURCE Calculated from data in G. Malorgio and A. Felice (2014) 'Trade and logistics: The fruit and vegetables industry', *Mediterra 2014*, CIHEAM Paris, France: 149–71 ◂www.ciheam.org/index.php/en/publications/mediterra-2014▸.

in 2010 was estimated at about 750 million tonnes, with the main producers being China (with 22% of world production), followed by Nigeria (11%), India (6%), Brazil and Indonesia (each at 4%). In Europe, production of the major root crop, potatoes, has been in decline for many years. Similarly, production of sweet potato has also shown a marked decline, being one-third of the level of 1980. However, this trend actually reflects a fall in the use of sweet potatoes in China for animal feed, which highlights difficulties in interpreting the food usage of such crops.

The international trade in fruit and vegetables is notoriously difficult to accurately document, particularly as many countries such as Singapore and Belgium act as transit centres and are recorded as both substantial importers and exporters.

Data published by the International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM) (Table 1.2) indicates that the 27 countries in the European Union (EU) make up the major importing and exporting region for fruit and vegetables, followed by the USA and China. Mexico, Turkey, Chile and Canada are also important exporters. Many developing countries have targeted fruit and vegetable production as a national export effort. This strategy has been aided by there being fewer trade barriers to the entry of fresh fruit and vegetables into developed countries than for many other agricultural commodities.

The need for postharvest technology

Fruit and vegetables are ideally harvested at optimum eating or visual quality. However, since they are living biological products, they will deteriorate after harvest. The rate of deterioration varies greatly between individual produce, depending on their overall rate of metabolism, but for many types of produce this deterioration can be very rapid. For simple marketing chains where produce is transferred from farm to end user in a short period, the rate of postharvest deterioration is of little consequence. However, with the increasing remoteness of production areas from population centres in both developing and developed countries, the proliferation of large urban centres with complex marketing systems and the growth in international trading, the time from the farm to the market can be considerable. Adding to this time delay between farm and end user is the deliberate storage of certain produce to capture a better return by extending the marketing period into a time of shorter supply. Thus, the modern marketing chain is creating increasing demands on produce and has created the need for postharvest techniques that allow retention of quality over increasingly long periods.

Extending the postharvest life while maintaining eating quality requires knowledge of all factors that result in loss of quality. The creation and use of this knowledge to develop affordable and effective technologies that minimise the rate of deterioration is the field of scientific, technical and social endeavour known as postharvest. The increased attention given to postharvest horticulture in recent years has come through the realisation that poor handling practices after harvest can cause large losses of produce that has already had substantial inputs of labour, materials and capital to grow. Informed opinion now suggests that increased emphasis should be placed on conservation after harvest, rather than endeavouring to further boost crop production, as this would appear to offer a better return for the available resources of labour, energy, capital and the environment. Postharvest improvements in developed economies are required to meet the ever-increasing quality standards and market expectations in a global trading environment. This global demand for fresh fruit and vegetables has created opportunities for farmers in less developed countries, but improved supply chain efficiency and final produce quality are necessary to realise the full benefit of these opportunities.

The actual causes of postharvest loss of fruit and vegetables are many but can be classified into two main categories. The first of these is physical loss, which can arise from mechanical damage or pest and disease damage. This can result in produce tissue being disrupted to a point where it is not acceptable for presentation, fresh consumption or processing. Physical loss can also arise from evaporation of intercellular water, which leads to a direct loss in weight (water). The resulting economic loss is primarily due to the reduced mass of produce but can also cause significant losses as a whole batch of the commodity can be rejected through wastage of a small proportion of individual items in that batch.

Loss of quality is the second cause of postharvest loss and this can be due to physiological and compositional changes that alter the appearance, taste or texture and make produce less desirable aesthetically to end users. These changes may arise from the normal metabolism of produce (e.g. senescence) or abnormal events (e.g. chilling injury) as a result of the postharvest environment. Economic losses are incurred in having to market poor quality produce at reduced prices. In many markets there is no demand for this second-class produce even at reduced prices, which can lead to a total economic loss even though it may still be edible.

In many tropical regions, which include a large proportion of the developing countries, these losses can assume considerable economic and social importance. In developed regions postharvest deterioration of fresh produce can be just as serious, although it often occurs due to different causes. As the value of fresh produce may increase many times from the farm to the retailer, the economic consequences of deterioration at any point along the chain are serious. When farms are located near towns and cities, poor handling practices are often less important because the produce is usually consumed before serious wastage can occur. Even in the tropical regions, production of some staple commodities is seasonal, and there is a need to store produce to meet requirements during the out of season markets. In many countries fresh fruit and vegetables are frequently grown at locations remote from the major centres of population. Millions of tonnes of produce are now transported daily over long distances both within countries and internationally. Fresh fruit and vegetables are important items of commerce and there is a huge investment of resources in transport, storage and marketing facilities designed to maintain a continuous supply of these perishable commodities. Postharvest technology aims to protect that investment.

While the magnitude of losses of horticultural produce during postharvest and marketing operations is widely acknowledged to be considerable, few studies have accurately quantified these losses. Part of the difficulty in quantifying postharvest losses is identifying the actual steps in the postharvest chain where the loss was induced. It is not uncommon for a physical or metabolic stress to be imposed on produce, but the visual deleterious action may not be evident until later in the marketing chain. For example, failure to properly cool the produce after harvest can advance general senescence, but visible symptoms such as loss of green colour may not occur for days or weeks. In addition, the visible cause of loss may not be the actual cause; for example, chilling injury of tomatoes is induced by prolonged storage at sub-optimal temperatures, but visual symptoms are usually secondary mould growth on the damaged tissues and not the chilling injury itself.

Postharvest technology

The ultimate role of postharvest technology is to devise and successfully apply cost-effective methods by which deterioration of produce is restricted as much as possible during the period between harvest and end use and to ensure that eating quality and maximum market value for the produce is achieved. This requires a thorough understanding of the structure, composition, biochemistry and physiology of horticultural produce, as postharvest technologies are mainly concerned with slowing down the rate of produce metabolism without inducing abnormal events. While there is a common underlying structure and metabolism, different types of produce can vary greatly in their response to specific postharvest situations. Appropriate postharvest technologies must be developed to cope with these differences. The variation in response can also be important between cultivars of the same produce and also often between maturities, growing areas or seasons. However, of most importance is the appropriate use of technology. The best postharvest solution many not be the most cost-effective or optimum for every specific supply chain. The optimum postharvest technology must meet the expectation of the customer at the least environmental and economic cost.

The principal technique in postharvest is to control the storage environment and handling conditions. As the rate of postharvest deterioration is greatly affected by temperature, temperature control is the most important environmental factor to manage. Fresh horticultural produce must be maintained within the temperature range encompassed by a lower limit of the freezing point of plant tissues (about –2°C to 0°C) and an upper limit when plant tissues start to collapse at about 40°C. The effects of temperature on horticultural produce are, however, not uniform over the range. Moreover, there are time/temperature relationships where produce can withstand abnormally high or low temperatures for a short period. Thus, detailed knowledge of the response of particular produce across the temperature range is essential to determine optimal storage temperature conditions. In general, the ideal postharvest temperature is just above the freezing point where metabolism is slowest, but other factors such as the onset of abnormal metabolism at reduced temperatures can limit the use of low temperatures. The beneficial effect of reduced temperature on suppression of microbial growth is also an important consideration in many postharvest systems.

Other important environmental conditions that can affect the quality and storage of produce are the concentration of certain gases and water vapour in the atmosphere around produce. Maintenance of a high relative humidity in the atmosphere is necessary to minimise water loss – a key quality factor since wilted or shrivelled produce has greatly reduced market value. The presence of ethylene in the atmosphere has long been of interest for postharvest handling as it initiates the ripening process in climacteric fruit and its management around non-climacteric fruit and vegetables is also important to inhibit senescence. The use of modified and controlled atmospheres utilising elevated carbon dioxide and reduced oxygen levels from the normal air atmosphere generally has a beneficial effect on produce metabolism, but logistical problems of adequately containing gas levels within the beneficial range have restricted its use to only a few commodities.

Physiological disorders arise from adverse postharvest and preharvest environmental conditions or mineral imbalances arising during growth, and can be a major problem in the handling and storage of produce. But the major issue for the storage and transport of fresh fruit and vegetables is microbial decay arising from a range of bacteria and fungi that can infect produce before and/or after harvest. These can be managed by ensuring that produce is not exposed to the causative factors and using control measures which have tended to focus on the use of synthetic chemicals. However, with current consumer concerns, much interest is now on the use of natural compounds or physical treatments.

The trade of horticultural produce across international borders, and sometimes within a country, is sometimes restricted owing to the presence of quarantine pests (such as fruit flies). In these instances, postharvest treatments such as cold treatment or fumigation, are sometimes used to disinfest the produce to kill the quarantine pest within the produce without affecting quality.

Apart from generating information on the effects of environmental conditions on particular produce, postharvest research must also ensure that this technology is user-friendly and cost-effective to enable the benefits of scientific knowledge to have commercial value. This can either be in the form of technology adaptation, such as development of the refrigerated container which created a mobile cool storage chamber, or the application of technical information to design new technology as in the use of vapour-heat treatments for insect disinfestation. Packaging is an essential component in every supply chain, as it provides protection to the produce from physical damage and contamination while meeting other marketing criteria.

A recent challenge for postharvest technology is the need for innovations to be environmentally sustainable both from an economic and a community perception perspective. There is international concern at government and individual level to limit the emission of greenhouse gases, and schemes to limit energy usage have often increased the cost of energy. Many current technologies are being reassessed to determine if energy usage can be reduced while maintaining shelf life. Another major challenge for postharvest is to reduce synthetic chemical use. The reassessment of physical treatments and generally regarded as safe (GRAS) compounds to control postharvest diseases and disorders will help satisfy consumers and reduce the risk of chemical residues.

Once the loss of quality and wastage in the postharvest chain is successfully managed, the next issue to consider is being responsive to market needs in terms of consumer expectations on quality, safety and presentation. Responsiveness to the market has forced marked changes in quality assessment. This was originally limited to grading operations in the packing house for size or weight, removal of defects and ensuring the correct labelling of containers but is now a total quality operation to ensure all market specifications are met and that the enterprise operates in the most efficient manner. Eating quality and final product quality are thus linked to profitability, and successful implementation requires a complete understanding of all factors that affect produce and the market environment. Thus, quality management starts in the field and continues until produce reaches the end user. Training of staff through the supply chain is now an integral part of quality management as individuals or work teams are empowered to take responsibility for ensuring predetermined quality criteria are met.

The minimal processing of fresh fruit and vegetables to generate products that are cut or lightly processed to make the original commodity more convenient for consumers has become an increasingly important segment on many supermarket shelves and in the growing food service industry. However, such processing invariably increases metabolism and renders produce more susceptible to microbial attack and adverse environmental conditions. Convenience marketing to a time-poor consumer has also extended to pre-packaging of a single produce or a range of produce such as leafy vegetables into an acceptable size retail unit. It is often a challenge to develop technology that retains quality in convenience products for the desired market period at a reasonable cost.

The use of molecular biology is of increasing interest to researchers to overcome specific postharvest problems. While a number of genetically modified (GM) fruit and vegetables have been developed, commercialisation has been almost non-existent as many consumers remain resistant to accepting GM foods. In the USA, the only GM produce on the market in 2015 with any impact was the Rainbow papaya, which is resistant to the ringspot virus and now accounts for 80% of the Hawaiian crop. GM sweet corn and zucchini squash are marketed in the USA but have little market share. No GM produce is allowed to be marketed in the EU. To begin to have any consumer acceptance or a reasonable chance of commercial success, GM produce must have a marked demonstrable benefit to growers, traders and consumers.

2
Structure and composition

Structure

While the terms 'fruit' and 'vegetables' are well understood, it is not always clear into which category a particular item of horticultural produce should be classed. A botanical definition of a fruit is the edible portion of a plant that contains the seed or its envelope, but a consumer definition is plant products with aromatic flavours and natural sweetness. Thus, consumer perception has resulted in various immature fruits such as zucchini, cucumber and beans, and even ripe fruit such as tomato, capsicum and eggplant, being considered as vegetables.

From a botanical perspective, Figure 2.1 shows the origins of various common fruits that comprise combinations of tissues that may include an expanded ovary, the seed and other plant parts such as the receptacle (apple, strawberry, cashew apple), bract and peduncle (pineapple). Most of the exaggerated developments of certain parts of the fruit structure arose naturally but have been accentuated by breeding and selection to maximise the desirable features of each fruit and minimise the superfluous features. Naturally seedless cultivars of some fruits (e.g. banana, grape, navel orange) and others induced by

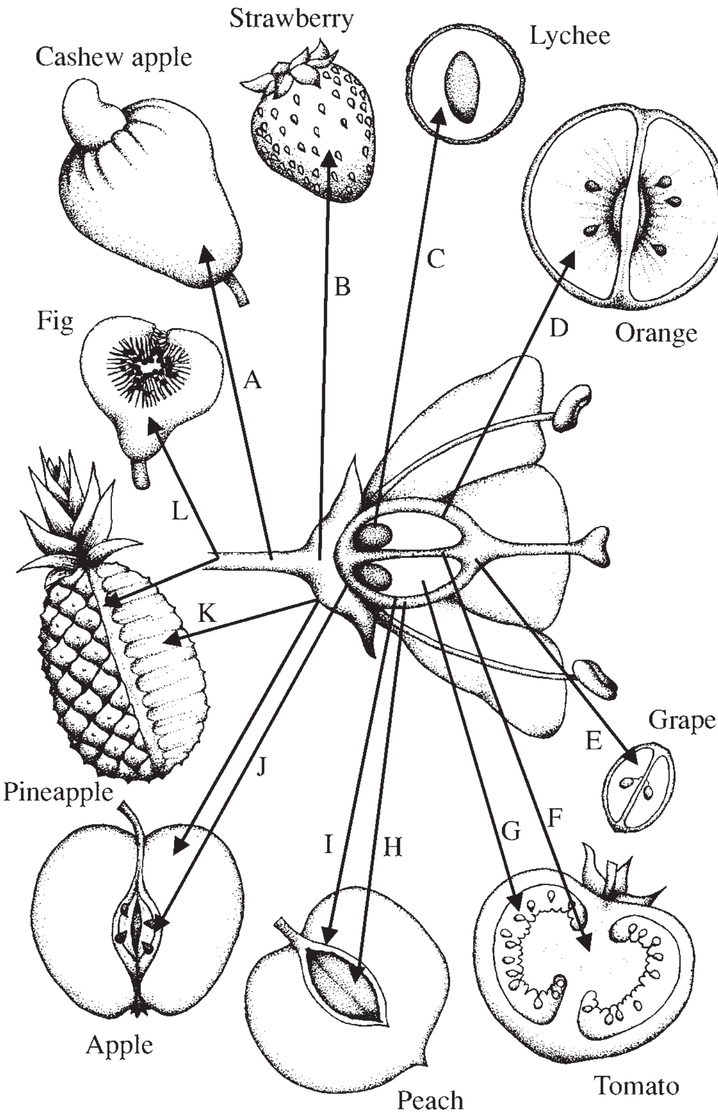


Figure 2.1 Derivation of some fruits from plant tissue. The letters indicate the tissues that comprise a significant portion of the fruit illustrated: (A) pedicel, (B) receptacle, (C) aril, (D) endodermal intralocular tissue, (E) pericarp, (F) septum, (G) placental intralocular tissue, (H) mesocarp, (I) endocarp, (J) carpels, (K) accessory tissue, (L) peduncle.

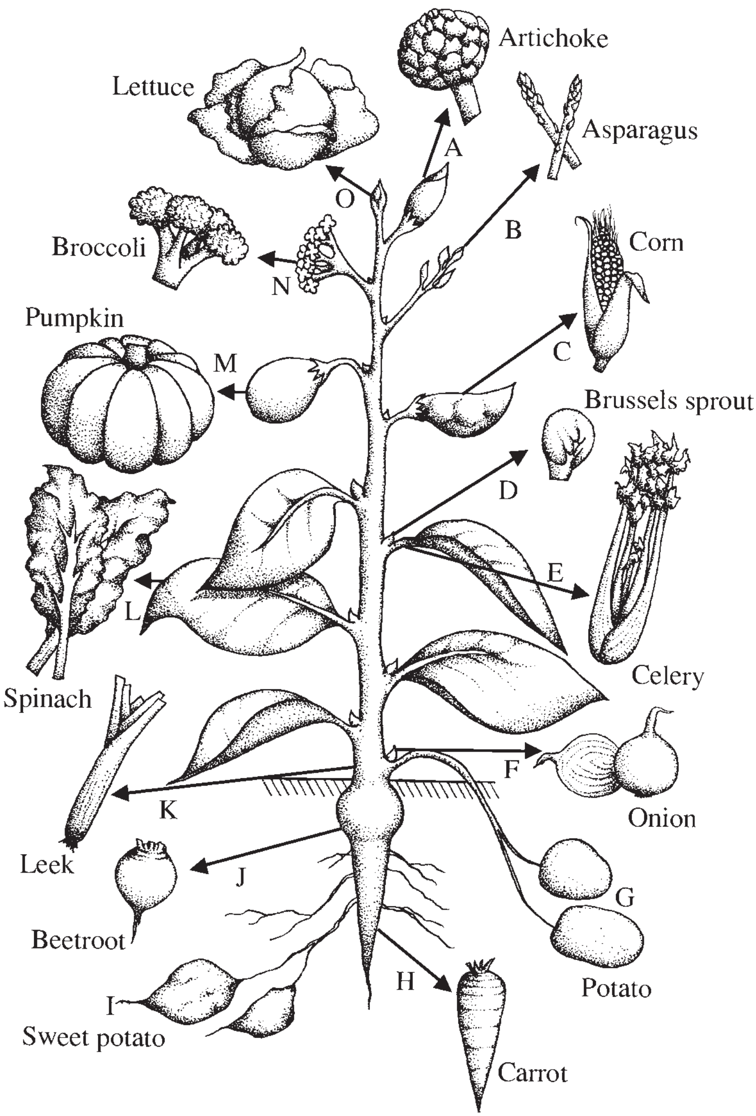


Figure 2.2 **Derivation of some vegetables from plant tissue.** The letters indicate the principal origins of representative vegetables as follows: (A) flower bud, (B) stem sprout, (C) seeds, (D) axillary bud, (E) petiole, (F) bulb (underground bud), (G) stem tuber, (H) swollen root, (I) swollen root tuber, (J) swollen hypocotyls, (K) swollen leaf base, (L) leaf blade, (M) fruit, (N) swollen inflorescence, (O) main bud.

breeding (e.g. watermelon) or management (e.g. persimmon) illustrate extreme development.

Vegetables do not represent any specific botanical grouping and exhibit a wide variety of plant structures. However, they can be grouped into three main categories: (1) seeds and pods; (2) bulbs, roots and tubers; and (3) flowers, buds, stems and leaves. In many instances, the structure giving rise to the particular vegetable has been highly modified compared with that structure on the 'ideal' plant. The derivation of some vegetables is shown in Figure 2.2. The plant part that gives rise to the vegetable will be readily apparent when most vegetables are visually examined. Some are a little more difficult to categorise, especially the tuberous organs developed underground. For instance, the potato is a modified stem structure, while other underground storage organs such as the sweet potato are simply swollen roots.

The structural origins of fruit and vegetables have a major bearing on the recommendations for their postharvest management. In general, above-ground structures develop natural wax coatings as they mature which reduce transpiration, whereas roots do not develop such coatings and therefore should be stored at high relative humidity (RH) to minimise water loss. Tuberous vegetables are equipped with a special capability to heal wounds caused by natural insect attack. This property is useful for minimising damage inflicted on tubers during harvesting.

Cellular components

The cells of fruit and vegetables are typical plant cells, the principal components of which are shown in Figure 2.3. An outline of the essential features or functions of these components is presented here, but more detailed explanations can be found in specialised texts.

Plant cells are bounded by a mostly rigid cell wall composed of cellulose fibres, and other polymers such as pectic substances, hemicelluloses, lignins and proteins. A layer of pectic substances forms the middle lamella and acts to bind adjacent cells together. Adjacent cells often have small communication channels, called plasmodesmata, which link their cytoplasmic masses. The cell wall is permeable to water and solutes. Important functions of the wall are to support the cell membrane, the plasmalemma, against the hydrostatic pressures of the cell contents which would otherwise burst the membrane; and to give structural support to the cell and the plant tissues.

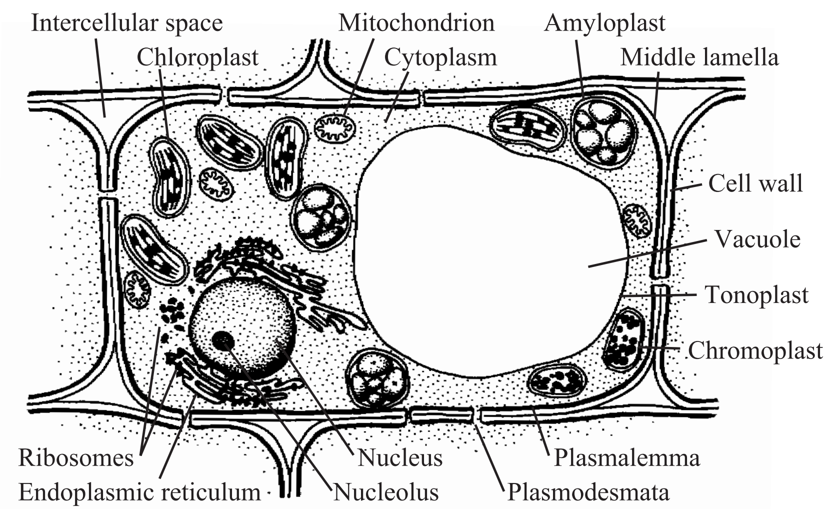


Figure 2.3 Diagrammatic representation of a plant cell and its constituent organelles

Within the plasmalemma, the cell contents comprise the cytoplasm and usually one or more vacuoles. The latter are fluid reservoirs containing various solutes, such as sugars, amino and organic acids, and salts; and are surrounded by a semi-permeable membrane, the tonoplast. Together with the semi-permeable plasmalemma, the tonoplast is responsible for maintaining the hydrostatic pressure of the cell, allowing the passage of water but selectively restricting the movement of solutes or macromolecules, such as proteins and nucleic acids. The resulting turgidity of the cell is responsible for the crispness in fruit and vegetables. The selective movement of various solutes between organelles and cell walls has a major role in the regulation of ripening and senescence.

The cytoplasm comprises a fluid matrix of proteins and other macromolecules and various solutes. Important processes occurring in this fluid part of the cytoplasm include the breakdown of storage reserves of carbohydrate by glycolysis (see Chapter 3) and protein synthesis. The cytoplasm also contains several organelles, which are membrane-bound bodies with specialised functions as follows:

1 The nucleus: this is the largest organelle and is the control centre of the cell, containing its genetic information in the form of DNA (deoxyribonucleic acid). It is bounded by a porous membrane that permits the movement of mRNA (messenger ribonucleic acid), the transcription product of the genetic code of DNA, into the cytoplasm where it is translated into proteins on the ribosomes.
2 The mitochondria: these contain the respiratory enzymes of the tricarboxylic acid (TCA) cycle (see Chapter 3) and the respiratory electron transport system which

synthesises adenosine triphosphate (ATP). Mitochondria utilise the products of glycolysis for energy production. Thus they form the energy powerhouse of the cell.

3 The chloroplasts: these are found in green cells and are the photosynthetic apparatus of the cell. They contain the green pigment chlorophyll and the photochemical apparatus for converting solar (light) energy into chemical energy through converting atmospheric carbon dioxide to sugars and other carbon compounds.

4 Other plastids, comprising chromoplasts that contain carotenoids which are the yellow-red pigments in many fruits, and amyloplasts which are the site of starch grain development.

Chemical composition and nutritional value

Considerable information now exists on the composition of individual fruit and vegetables, particularly in terms of constituents with nutritional value. This data can be readily accessed through the many national and regional tables of food composition available on paper or electronically. However, care should be taken in the application of such data due to the considerable differences in composition between cultivars and the effects of maturity, season, locality and storage between and within countries. The overview of fruit and vegetable constituents that follows is taken from the Australian Food Composition database – NUTTAB 2010[1] – with the values cited being on a fresh weight basis of the edible portion.

1 The Australian Food Composition database: <www.foodstandards.gov.au/science/monitoringnutrients/nutrientables/pages/default.aspx>.

Water

Most fruit and vegetables contain more than 80 g/100 g water, with some tissues – such as those in cucumber, lettuce and melons – containing about 95 g/100 g water. Starchy tubers and seeds (e.g. yam, cassava and corn) contain less water, but even they usually comprise more than 50 g/100 g water. Quite large variations in water content can occur within a species, since the water content of individual cells varies considerably. The actual water content is dependent on the availability of water to the tissue at the time of harvest; hence the water content of produce will vary during the day if there are diurnal fluctuations in temperature and relative humidity. For most produce, it is desirable to harvest when the maximum possible water content is present as this gives a crisp texture. Hence the time of harvest can be an important consideration particularly with leafy vegetables, which exhibit large and rapid variations in water content in response to changes in their environment.

Carbohydrates

Carbohydrates are generally the most abundant group of constituents after water. They can be present across a wide molecular weight range from simple sugars to complex polymers which may comprise many hundreds of sugar monomeric units. Carbohydrates can account for 2–40 g/100 g of produce tissue, with low levels being found in some cucurbits (e.g. cucumber) and high levels in vegetables that accumulate starch (e.g. cassava).

The main sugars present in fruit and vegetables are sucrose, glucose and fructose, with the predominant sugar

Table 2.1 Fruit and vegetables with high sugar levels (g/100 g)

Produce	Total sugars	Glucose	Fructose	Sucrose
Banana	17	4	4	10
Jackfruit	16	4	4	8
Litchi	16	8	8	1
Persimmon	16	8	8	0
Rambutan	16	3	3	10
Grape	15	8	8	0
Custard apple	15	5	6	4
Pomegranate	14	8	6	0
Carambola	12	1	3	8
Mango	12	1	3	8

varying in different produce. Glucose and fructose occur in all produce and are often present at a similar level, while sucrose is only present in about two-thirds of produce. Produce with the highest sugar levels (Table 2.1) are mainly tropical and subtropical fruit, with grape the only temperate fruit listed and no vegetables listed. Beetroot contains the highest sugar content among the vegetables, at about 8 g/100 g, with sucrose being the only sugar present. Much of the sensory appeal of fruit is due to the sugar content as sugars produce a sweet taste, which is considered to be one of the universal innate human taste preferences.

Humans can digest and utilise sugars and starch as energy sources; hence vegetables with a high starch content are important contributors to the daily energy requirement of people in many societies. Produce such as cassava and yam commonly contain >20 g/100 g as starch, with other starchy produce containing >10 g/100 g starch. While an over-dependence on starchy vegetables is undesirable, as they cannot supply enough of certain essential nutrients, consumers in developed countries are being encouraged to eat more starch, or complex carbohydrates as it is now called, although in these countries cereals rather than fruit and vegetables are the major source of dietary starch.

Concern over the rise of diabetes in many societies has focused attention on the amount and type of carbohydrates in the diet and how they affect blood glucose levels. The concept of a glycaemic index (GI) of foods is now well established, where the elevation of blood glucose arising from ingestion of a glucose solution is rated as 100. The GI of fruit and vegetables varies widely and ranges from 22 (cherries) to 97 (parsnip). Of interest is that white bread, a common source of starch in Western countries, has a GI of 70 whereas starchy vegetables such as potato and sweet potato have a GI of 55–60.

A substantial proportion of carbohydrate is present as dietary fibre, which is not digested in the human upper intestinal system but is either metabolised in the lower intestines or passes from the body in the faeces. Cellulose, pectic substances and hemicelluloses are the main carbohydrate polymers that constitute fibre. Lignin, a complex polymer of aromatic compounds linked by propyl units, is also a major component of dietary fibre. Dietary fibre is not digested, as humans are not capable of secreting the enzymes necessary to break down the polymers to the basic monomeric units that can be absorbed by the intestinal tract.

Starch and cellulose have the same chemical composition, as they are synthesised from D-glucose units, but the bonding between the monomers differs. Starch comprises *a*-1,4 linkages, which are hydrolysed by a range of amylase enzymes secreted by humans; cellulose is formed with ß-1,4 linkages but cellulase enzymes are not produced by humans. Similarly, the enzymes necessary to hydrolyse the pectins and hemicelluloses to smaller units are lacking in humans. Dietary fibre was once considered to be an unnecessary component in the diet, although it was known to relieve constipation. But increased consumption of dietary fibre is now actively promoted by health agencies.

Protein

The level of protein in fresh fruit and vegetables is low, at about l g/100 g protein in fruit and about 2 g/100 g in most vegetables, with the most abundant protein sources being the *Brassica* vegetables which contain 3–5 g/100 g and the legumes at about 5 g/100 g protein. The protein is mostly functional (e.g. as enzymes) rather than a storage pool as in grains and nuts. Their relatively low level means that fresh fruit and vegetables are not an important source of protein in the diet.

Lipids

Lipids comprise less than 1 g/100 g of most fruit and vegetables and are associated with protective cuticle layers on the surface of the produce and with cell membranes. The avocado and olive (used as a fresh vegetable) are exceptions, having respectively about 20 g and 15 g/100 g lipid present as oil droplets in the cells. The generally low lipid content is seen as a positive factor in combating the rise of heart disease in the community. Even those types of produce, such as avocado, that have relatively high lipid contents contain mostly monounsaturated fatty acids. Monounsaturated fatty acids are associated with the beneficial effects of consuming a 'Mediterranean diet' and hence are considered protective against heart disease.

Organic acids

Most fruit and vegetables contain organic acids at levels in excess of that required for the operation of the TCA cycle and other metabolic pathways. The excess is generally stored in the vacuole, away from other cellular components. Lemon, lime, passionfruit and black currant often contain over 3 g/100 g of organic acids. The dominant acids in produce are usually citric and malic acid. Other organic acids that are dominant in certain commodities are tartaric acid in grapes, oxalic acid in spinach and isocitric acid in blackberries. Apart from their biochemical importance, organic acids contribute greatly to taste, particularly of fruit – with a balance of sugar and acid giving rise to the desirable taste of each produce. This is discussed in more detail in Chapter 10.

Vitamins and minerals

Vitamin C (ascorbic acid) is the most important micronutrient in fruit and vegetables, as they supply virtually all dietary vitamin C (approximately 90%). Vitamin C helps the body make collagen and hence is important for the repair and maintenance of skin, cartilaginous tissue and blood vessels. The daily requirement is about 50 mg, and many commodities contain this amount of vitamin C in less than 100 g of fresh tissue.

Fruit and vegetables may also be important nutritional sources of vitamin A and folic acid, commonly supplying about 40% of daily requirements. Vitamin A is required by the body

Table 2.2 Levels of vitamin C, vitamin A and folic acid in some fruit and vegetables

Commodity	Vitamin C (mg/100 g)	Commodity	Vitamin A, β-carotene equivalent (mg/100 g)	Commodity	Folic acid (μg/100 g)
Black currant, guava	200	Carrot	10.0	Spinach	80
Chilli	150	Sweet potato	6.8	Broccoli	50
Broccoli, brussels sprout	100	Parsley	4.4	Brussels sprout	30
Papaya	80	Spinach	2.3	Cabbage, lettuce	20
Kiwi fruit	70	Mango	2.4	Banana	10
Citrus, strawberry	40	Red chilli	1.8	Most fruits	<5
Cabbage, lettuce	35	Tomato	0.3		
Banana, potato, tomato	20	Banana	0.1		
Apple, peach	10				

to maintain the structure of the eye; a prolonged deficiency of vitamin A can eventually lead to blindness. The active vitamin A compound, retinol, is not present in produce, but some carotenoids such as ß-carotene can be converted to retinol in the human body. Only about 10% of the carotenoids known to be in fruit and vegetables are precursors of vitamin A.

Folic acid is involved in RNA synthesis, and a deficiency will result in anaemia. Folic acid deficiency during early pregnancy has been associated with foetal spina bifida and various countries fortify certain foods with folic acid to minimise the risk. Green leafy vegetables are a good source of folic acid, with the intensity of green colour acting as a good guide to the folic acid content. Table 2.2 shows the range of levels of vitamins C and A and folic acid in some fruit and vegetables. Maintenance of these vitamins during handling and storage should be considered, particularly when the produce will be consumed by people on marginally sufficient diets.

The major mineral in fruit and vegetables is potassium, which is present at more than 200 mg/100 g in most produce. The highest levels are in green leafy vegetables, with parsley containing about 1200 mg/100 g; but about 20 vegetables contain 400–600 mg/100 g. Health authorities in many countries are urging increased consumption of potassium to counter the effects of sodium in the diet, and fruit and vegetables are the richest natural food source of potassium.

Many other vitamins and essential minerals are present in fruit and vegetables, but their contribution to total dietary requirements is generally of minor importance. Iron and calcium may be present at nutritionally significant levels, although often in a form that is unavailable for absorption by humans (e.g. most of the calcium in spinach is present as calcium oxalate, which is only poorly absorbed).

The nutritional value of various fruit and vegetables depends not only on the concentration of nutrients in the produce but also on the amount of such produce consumed in the diet. An attempt to equate these factors and show the relative concentration of ten major vitamins and minerals in some fruit and vegetables and their importance in the typical US diet in the 1970s is shown in Table 2.3. Although tomatoes and oranges contain relatively low levels of nutrients, they make

Table 2.3 Relative concentration of ten vitamins and minerals in fruit and vegetables and the relative contribution of vitamins and minerals these commodities make to the US diet

Nutrient concentration		Contribution of nutrients to diet	
Crop	**Rank**	**Crop**	**Rank**
Broccoli	1	Tomato	1
Spinach	2	Orange	2
Brussels sprout	3	Potato	3
Lima bean	4	Lettuce	4
Pea	5	Sweet corn	5
Asparagus	6	Banana	6
Artichoke	7	Carrot	7
Cauliflower	8	Cabbage	8
Sweet potato	9	Onion	9
Carrot	10	Sweet potato	10
Sweet corn	12	Pea	15
Potato	14	Spinach	18
Cabbage	15	Broccoli	21
Tomato	16	Lima bean	23
Banana	18	Asparagus	25
Lettuce	26	Cauliflower	30
Onion	31	Brussels sprout	34
Orange	33	Artichoke	36

SOURCE Adapted from C.M. Rick (1978) 'The tomato', *Scientific American* 239(2): 66–76.

a major contribution to the US diet because of the large per capita consumption. Carrot and sweet potato are the only produce in the top 10 ranked on nutrient concentration that are also in the top 10 dietary contributors.

Antioxidants

A range of compounds present in fruit and vegetables possess antioxidant properties and some, such as vitamin C, have been used for many years in food processing to prevent oxidation of food constituents by preferentially interacting with free radicals. Interest in the possible health benefits of many compounds with antioxidant properties has in recent years extended to claims of a reduced risk of certain degenerative diseases including cancers, cardiovascular disease, diabetes, arthritis and ocular degeneration. Groups of produce with high *in vitro* antioxidant properties include berries, stone fruit, apples, and *Brassica* and *Allium* vegetables. However, there remains conjecture whether such compounds are absorbed from the digestive system at levels that would have a beneficial health effect and even the relevance of *in vitro* properties to body metabolism.

Volatiles

All fruit and vegetables produce a range of small molecular-weight compounds (molecular weight less than 250) that possess some volatility at ambient temperatures. These compounds are not important quantitatively (normally less than 10 mg/100 g are present), but they are important in producing the characteristic flavour and aroma of fruit and, to a lesser extent, of vegetables. Most fruit and vegetables each contain more than 100 different volatiles, and the number of compounds identified in particular produce is continually increasing as the sensitivity of the analytical techniques for identification improves. The compounds are mainly esters, alcohols, acids and carbonyl compounds (aldehydes and ketones). Many of

Table 2.4 Distinctive volatile components of the aroma of some fruit and vegetables

Produce	Compound
Apple – 'Fuji'	Ethyl 2-methyl butanoate, 2-methyl butyl acetate, hexyl acetate
– 'Elstar'	Ethyl butanoate, ethyl 2-methyl butanoate
– 'Pink Lady'	Hexyl acetate, hexyl 2-methyl butanoate, hexyl hexanoate, hexyl butanoate, 2-methylbutyl acetate
Banana – green	2-Hexenal
– ripe	Eugenol
– overripe	Isopentanol
Mandarin – 'Clemenules'	3-Pentanone, β-ionone
Melon	Ethyl 2-methyl propyl acetate
Orange – 'Navel'	Nonyl acetate, 3-carene
Cucumber	2,6-Nonadienal
Cabbage – raw	Allyl isothiocyanate
– cooked	Dimethyl disulphide
Mushroom	l-Octen-3-ol, lenthionine
Potato	2-Methoxy-3-ethyl pyrazine, 2,5-dimethyl pyrazine
Radish	4-Methylthio-trans-3-butenyl isothiocyanate
Strawberry	2,5-dimethyl-4-hydroxy-3(2H)-furanone

SOURCE Adapted from D.K. Salunkhe and J.Y. Do (1977) 'Biogenesis of aroma constituents of fruit and vegetables', *CRC Crit. Rev. Food Sci. Nutr.* 8: 161–90; and M.A. El Hadi, F.J. Zhang, F.F. Wu, C.H. Zhou and J. Tao (2013) 'Advances in fruit aroma volatile research', *Molecules* 18(7): 8200–29. doi: 10.3390/molecules18078200.

these compounds, such as ethanol, are common to all fruit and vegetables while other compounds are specific to an individual or species (e.g. esters are common constituents of most ripe fruits while sulphur-containing volatiles are present in many *Brassica* vegetables and tomatoes).

Definitive studies correlating consumer recognition of the produce with its volatile profile have shown that only a small number of compounds are responsible for consumer recognition of that commodity. In most fruit and vegetables the characteristic aroma is due to the presence of one or two compounds. Table 2.4 gives the key compounds claimed to be responsible for the characteristic aromas of some fruit and vegetables. Practically all the compounds mentioned in Table 2.4 are minor components of the aroma fraction. The olfactory senses in humans are thus extremely sensitive. The threshold concentration or minimum concentration at which the odour of ethyl 2-methylbutyrate, the main characteristic odour of apple, can be detected organoleptically was found at 0.001 μL/L. This means that for an apple of 100 g this characteristic odour can be recognised if only 0.01 μL of ethyl 2-methylbutyrate is present. For the characteristic odour to be desirable, it must also be in the correct concentration. At different stages of maturation, different compounds become the dominant component of flavour.

3
Physiology and biochemistry

An understanding of the postharvest handling of horticultural produce requires an appreciation that fruit and vegetables are 'living' structures. It is readily accepted that produce is a living, biological entity when it is attached to the growing parent plant in its agricultural environment. But even after harvest, the produce is still living as it continues to perform most of the metabolic reactions and maintain the physiological systems that were present when it was attached to the plant.

An important feature of plants and therefore of fruit and vegetables is that they respire by taking up oxygen and giving off carbon dioxide and heat. They also transpire; that is, lose water. While attached to the plant, the losses due to respiration and transpiration are replaced from the flow of sap, which contains water, photosynthates (principally sucrose and amino acids) and minerals. However, respiration and transpiration continue after harvest, and since the produce is now removed from a source of water, photosynthates and minerals, it is dependent entirely on its own food reserves and moisture content. Therefore losses of respirable substrates and moisture are not made up and deterioration commences. In other words, harvested fruit and vegetables are perishable.

This chapter will discuss the postharvest physiological and biochemical changes that occur during ripening and senescence of fruit and vegetables.

Physiological development

The life of fruit and vegetables can be conveniently divided into three major physiological stages following initiation or germination. These are: (1) growth, (2) maturation, and (3) senescence (Figure 3.1). However, there are no clear distinctions between the various stages. Growth involves cell division and subsequent cell enlargement, which accounts for the final size of the produce. Maturation usually commences before growth ceases and includes different activities in different commodities. Growth and maturation are often collectively referred to as the development phase. Senescence is defined as the period when anabolic (synthetic) biochemical processes give way to catabolic (degradative) processes, leading to ageing and finally death of the tissue. Ripening, a term reserved for fruit, is generally considered to begin during the later stages of maturation and to be the first stage of senescence. The change from growth to senescence is relatively easy to delineate. Often the maturation phase is described as the time between these two stages, without any clear definition on a biochemical or physiological basis.

Development and maturation of fruit are completed only when it is attached to the plant, but ripening and senescence may proceed on or off the plant. Fruits are generally harvested either when mature or when ripe, although some fruits such as zucchini that are consumed as vegetables may be harvested even before maturation has commenced. Vegetables are harvested over a wide range of physiological ages; that is, from a time

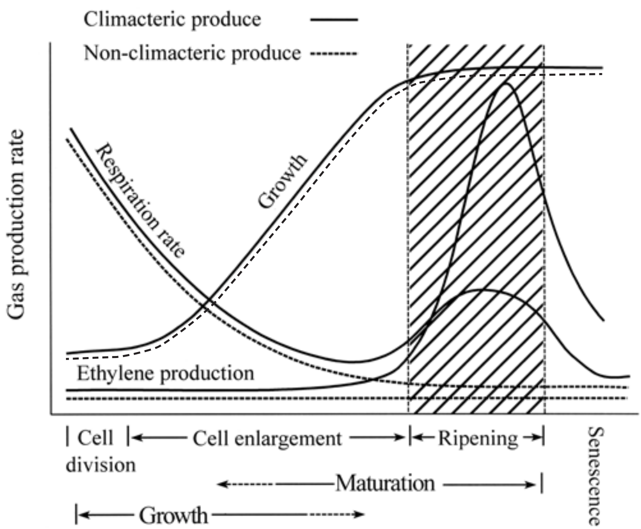


Figure 3.1 Growth, respiration and ethylene production patterns of climacteric and non-climacteric plant organs

well before the commencement of maturation through to the commencement of senescence (see Figure 10.2) but of course the ripening stage does not occur.

Fruit ripening

Ripening is a dramatic event in the life of a fruit as it transforms a physiologically mature but inedible plant organ into a visually attractive olfactory and taste sensation. Ripening is a complex set of changes, many of which probably occur independently of one another. It could be argued from a developmental biology perspective that the surrounding fruit tissue is protecting the seed during the development and maturation phases. Ripening can then be viewed as the process whereby degradation of the flesh allows the mature seed to be released for germination. Similarly, the onset of various physiological disorders during cool storage could be a seed-release mechanism, with cool storage being the simulation of the wintering period required by some temperate fruit before their seeds are activated for germination. Changes in colour, texture, taste and aroma attributes during ripening may facilitate seed release by attracting animals, birds and insects to disturb the fruit tissue.

Of the many changes that occur during ripening, postharvest technology has focused on the changes in ethylene and respiration in attempts to develop an explanation of the mechanism of fruit ripening.

Physiology of respiration

Respiration can be described as the oxidative breakdown of the more complex materials normally present in cells, such as starch, sugars and organic acids, into simpler molecules, such as carbon dioxide and water, with the concurrent production of energy and other molecules which can be used by the cell for synthetic reactions. Respiration can occur in the presence of oxygen (aerobic respiration) or in the absence of oxygen (anaerobic respiration, sometimes called fermentation).

The respiration rate of produce is an excellent indicator of metabolic activity of the tissue and thus is a useful guide to the potential storage life of the produce. If the respiration rate of a fruit or vegetable is measured – as either oxygen consumed or carbon dioxide evolved – during the course of its development, maturation, ripening and senescent periods, a characteristic respiratory pattern is obtained. Respiration rate per unit weight is highest for the immature fruit or vegetable and then steadily declines with age (Figure 3.1).

A significant group of fruits that includes tomato, mango, banana and apple, shows variation from the described respiratory pattern in that they undergo a pronounced increase in respiration coincident with ripening (Figure 3.2). Such an increase in respiration is known as a respiratory climacteric, and this group of fruits is known as the climacteric class of fruits. The intensity and duration of the respiratory climacteric, first described in 1925 for the apple and soon after found in many other fruit, varies widely amongst fruit species as depicted in

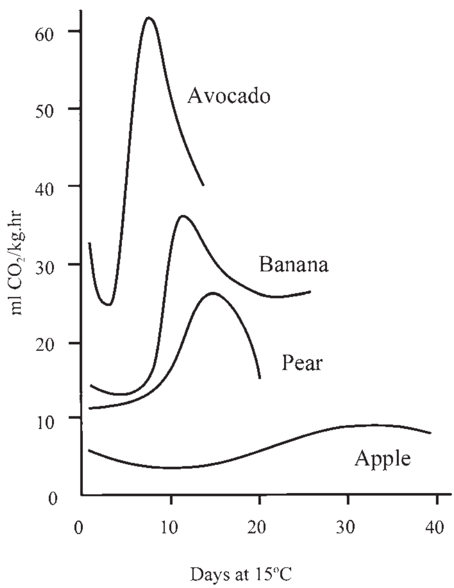


Figure 3.2 Respiratory patterns of some harvested climacteric fruits

SOURCE J.B. Biale (1950) 'Postharvest physiology and biochemistry of fruits', *Annual Review of Plant Physiology* 1: 183–206. (Used with permission.)

Figure 3.2. The commencement of the respiratory climacteric coincides approximately with the attainment of maximum fruit size (Figure 3.1), and it is during the climacteric that all the other changes characteristic of ripening occur. The respiratory climacteric, as well as the complete ripening process, may proceed while the fruit is either attached to or detached from the plant (except for avocado, which will only ripen when detached from the plant).

Fruits such as citrus, pineapple and strawberry, that do not exhibit a respiratory climacteric, are known as the non-climacteric class of fruit. Non-climacteric fruit exhibit most of the ripening changes, although these usually occur more slowly than those of the climacteric fruits. Table 3.1 lists some common climacteric and non-climacteric fruits. All vegetables can also be considered to have a non-climacteric type of respiratory pattern. The division of fruit into two classes on the basis

Table 3.1 Classification of some fruit according to their respiratory behaviour during ripening

Climacteric fruits	Non-climacteric fruits
Apple	Cherry (sweet and sour)
Avocado	Cranberry
Banana	Cucumber
Cherimoya	Grape
Fig	Lemon
Kiwi fruit	Loquat
Mango	Mandarin
Muskmelon (melon)	Orange
Papaya (pawpaw)	Pineapple
Passionfruit	Pomegranate
Peach	Strawberry
Tomato	Tamarillo (tree tomato)

of their respiratory pattern is an arbitrary classification and there is some overlap, but this classification has served to stimulate considerable research to discover the biochemical control of the respiratory climacteric.

Effect of ethylene

Climacteric and non-climacteric fruits may be further differentiated by their response to applied ethylene and by their pattern of ethylene production during ripening. It has been clearly established that all fruits produce small quantities of ethylene during development. However, coincident with ripening, climacteric fruits produce much larger amounts of ethylene than

Table 3.2 Internal ethylene concentrations measured in some climacteric and non-climacteric fruits

Fruit	Ethylene (μL/L)
Climacteric	
Apple	25–2500
Pear	80
Peach	0.9–20.7
Avocado	28.9–74.2
Mango	0.04–3.0
Passionfruit	466–530
Plum	0.14–0.23
Non-climacteric	
Lemon	0.11–0.17
Lime	0.30–1.96
Orange	0.13–0.32
Pineapple	0.16–0.40

SOURCE S.P. Burg and E.A. Burg (1962) ‘The role of ethylene in fruit ripening’, *Plant Physiology* 37: 179–89. (Used with permission.)

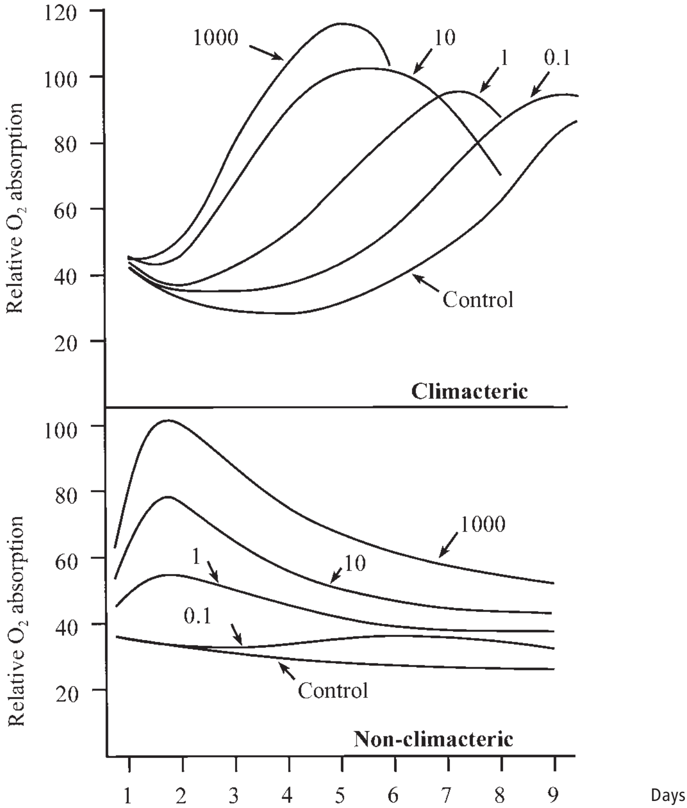


Figure 3.3 **Effects of applied ethylene on respiration of climacteric and non-climacteric fruits**

SOURCE J.B. Biale (1964) 'Growth, maturation, and senescence in fruits', *Science* 146: 880–88. (Used with permission.)

non-climacteric fruits. This difference between the two classes of fruit is further exemplified by the internal ethylene concentration found at several stages of development and ripening (Table 3.2). The internal ethylene concentration of climacteric fruits varies widely, but that of non-climacteric fruits changes little during development and ripening. Ethylene applied at a concentration as low as 0.1 microlitre per litre for one day is normally sufficient to hasten full ripening of climacteric fruit (Figure 3.3), but the magnitude of the climacteric is relatively independent of the concentration of applied ethylene. This is the basis of commercial ripening of bananas (Chapter 11). In contrast, applied ethylene merely causes a transient increase in the respiration of non-climacteric fruits, where the magnitude of the increase is dependent on the concentration of ethylene (Figure 3.3). Moreover, the rise in respiration in response to ethylene may occur more than once in non-climacteric fruits in contrast to the single respiration increase in climacteric fruits.

Physiochemical changes during fruit ripening

Colour

Colour is the most obvious change that occurs in many fruits and is often the major criterion used by consumers to determine whether the fruit is ripe or unripe. The most common change is the loss of green colour. The green colour is due to the presence of chlorophyll and the loss of green colour is due to degradation of the chlorophyll structure. The principal agents responsible for this degradation are pH changes (mainly due to leakage of organic acids from the vacuole), oxidative systems and chlorophyllases (Figure 3.4). Loss of colour depends on one or all of these factors acting in sequence to destroy the chlorophyll structure. With a few exceptions, for example, the avocado, kiwifruit and Granny Smith apple, climacteric fruits show rapid loss of green colour on ripening.

Many non-climacteric fruits also exhibit a marked loss of green colour with attainment of optimum eating quality; for example, citrus fruit in cooler temperate climates (but not in tropical climates).

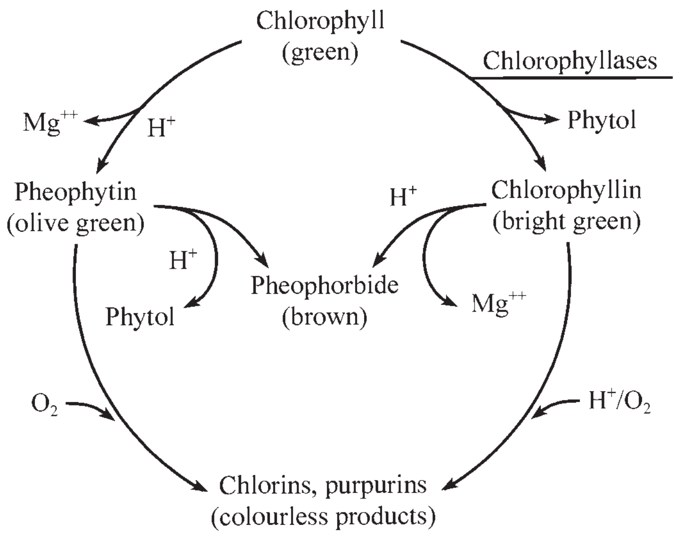


Figure 3.4 Some pathways for the degradation of chlorophyll

The disappearance of chlorophyll is often associated with the synthesis and/or revelation of pigments ranging from yellow to red. Many of these pigments are carotenoids, which are unsaturated hydrocarbons with generally 40 carbon atoms and which may have one or more oxygen atoms in the molecule. Carotenoids are stable compounds and remain intact in the tissue even when extensive senescence has occurred. Carotenoids may be synthesised during the development stages on the plant but are masked by the presence of chlorophyll.

Following the degradation of chlorophyll, the carotenoid pigments become visible. With some produce, carotenoid synthesis occurs concurrently with chlorophyll degradation. Banana peel is an example of the former system and tomato of the latter.

Anthocyanins provide many of the red-purple colours of fruit and vegetables. Anthocyanins are water-soluble phenolic glucosides that can be found in the cell vacuoles of fruit and vegetables such as cherry and beetroot, but are often located in the epidermal layers as with apple and grape. Anthocyanins can produce strong colours, which often mask the colour of carotenoids and chlorophyll.

Carbohydrates

The largest quantitative change associated with ripening is usually the breakdown of carbohydrate polymers, such as the near total conversion of starch to sugars. This alters both the taste and the texture of the fruit. The increase in sugar renders the fruit much sweeter and therefore more acceptable. Even with non-climacteric fruits, the accumulation of sugar is associated with the development of optimum eating quality, although the sugar may be derived from the sap imported into the fruit rather than from the breakdown of starch reserves of the fruit.

The breakdown of polymeric carbohydrates, especially pectic substances and hemicelluloses, weakens cell walls and the cohesive forces binding cells together. In the initial stages, the texture becomes more palatable, but eventually the plant structures disintegrate. Protopectin is the insoluble parent form of pectic substances. In addition to being a large polymer, it is cross-linked to other polymer chains with calcium bridges and is bound to other sugars and phosphate derivatives to form an extremely large polymer. During ripening and maturation, protopectin is gradually broken down to lower molecular weight fractions, which are more soluble in water. The rate of degradation of pectic substances is directly correlated with the rate of softening of fruit.

Organic acids

Usually organic acids decline during ripening as they are used in respiration or converted to sugars. Acids can be considered as a reserve source of energy to the fruit and would therefore be expected to decline during the greater metabolic activity that occurs during ripening. There are exceptions, such as bananas, where the highest acid level is attained at the fully ripe stage, but the level is not high at any stage of development compared to other produce.

Aroma

Aroma plays an important part in the development of optimal eating quality in most fruit. Aroma occurs because of the many volatile organic compounds (often known as volatiles) that are synthesised during the ripening phase. The total amount of carbon involved in the synthesis of volatiles is less than 1% of that expelled as carbon dioxide. The major volatile formed is ethylene, which accounts for about 50–75% of the total carbon in the volatiles; ethylene does not contribute to typical fruit aromas. The amount of aroma compounds is therefore extremely small. Chapter 2 discussed the nature of these volatile compounds. Non-climacteric fruits also produce volatiles during the development of optimum eating quality.

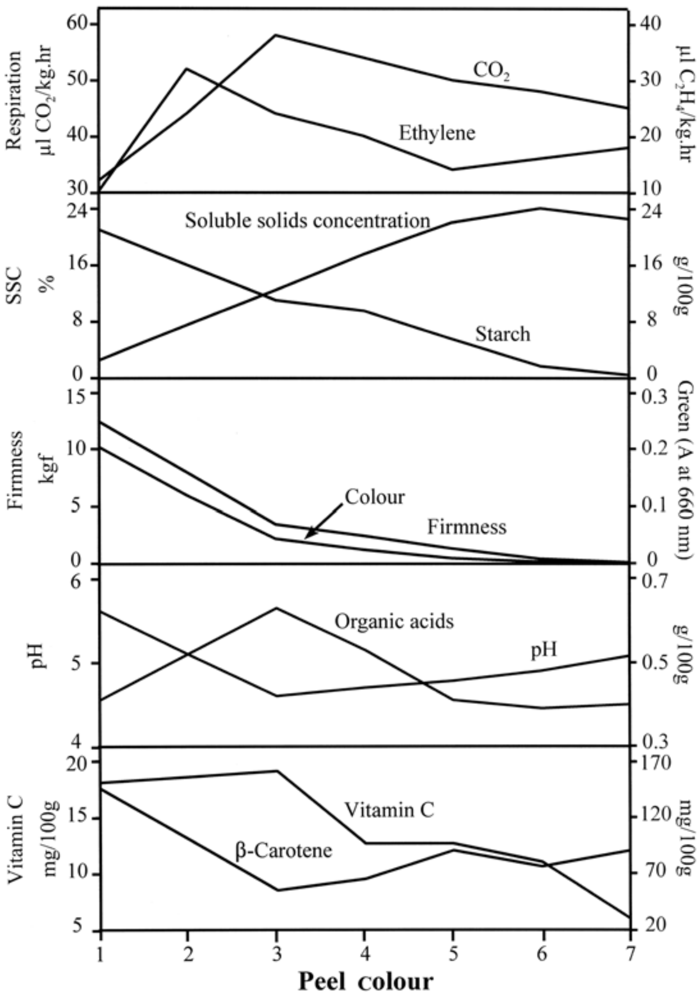


Figure 3.5 Physiochemical changes that occur during ripening of Cavendish banana (cultivar Williams). The peel colour stages indicate the change from green (stage 1) to full yellow (stage 6), and finally to a stage when skin spotting occurs (stage 7). Williams bananas take about eight days to progress from stage 1 to stage 7 at 20°C.

SOURCE Adapted from R.B.H. Wills, J.S.K. Lim and H. Greenfield (1984) 'Changes in chemical composition of "Cavendish" banana (*Musa acuminata*) during ripening', *Journal of Food Biochemistry* 8: 69–77.

While the sequence of changes during ripening varies between different fruit, Figure 3.5 illustrates the time sequence that occurs in bananas during ripening, with skin colour taken as the index of ripening. It can be seen that an increase in ethylene precedes an increase in respiration and the peak value for both ethylene and respiration occurs well before the fruit is ripe enough to eat. The peak production of ethylene is coincident with the onset of the conversion of starch to sugars and a decrease in pulp firmness. The total amount of acids in ripe fruit is similar to that in green fruit, while the level of vitamin C decreases during ripening.

Physiochemical changes during maturation of vegetables

Vegetables generally show no sudden increase in metabolic activity that parallels the onset of the climacteric in fruit, unless sprouting or regrowth is initiated. The process of germination is sometimes deliberately applied to some seeds (e.g. mung beans), and the sprouted product is the marketed vegetable. Apart from obvious anatomical changes during sprouting, considerable compositional changes occur. The sugar level increases markedly as a result of the rapid conversion of starch.

Vegetables can be divided into three main groups: (1) seeds and pods; (2) flowers, buds, stems and leaves; and (3) bulbs, roots and tubers. Some fruits are also consumed as vegetables; they may be either ripe (tomato, eggplant) or immature (zucchini, cucumber, okra).

Seeds and pods, if harvested fully mature, as is the practice with cereals, have low metabolic rates because of their low water content. In contrast, all seeds consumed as fresh vegetables (e.g. sweet corn) have high levels of metabolic activity, because they are harvested at an immature stage, often with the inclusion of non-seed material; for example, bean pod (pericarp). Eating quality is determined by flavour and texture and not by physiological age. Generally the seeds are sweeter and more tender at an immature stage. With advancing maturity, the sugars are converted to starch with the resultant loss of sweetness, the water content decreases and the amount of fibrous material increases. Seeds for consumption as fresh produce are harvested when the water content is about 70%; in contrast, dormant seeds are harvested when the water content is less than 15%.

Edible flowers, buds, stems and leaves vary greatly in metabolic activity and hence in rate of deterioration. Stems and leaves often senesce rapidly and so lose their attractiveness and nutritive value. The most visible sign of senescence is generally degreening, resulting in yellowing due to underlying carotenoid pigments. Texture often becomes the dominant characteristic that determines both the harvest date and quality, with loss of turgor due to water loss causing loss of texture. The natural flavour is often of less importance than texture, as many of these vegetables are cooked and salt or spice is added. Growth processes such as cell division and expansion, and protein and carbohydrate synthesis usually cease and the metabolism goes into a catabolic or degradative mode.

Bulbs, roots and tubers are storage organs that contain food reserves that are required when growth of the plant is resumed (they are often held for the purpose of propagation). When harvested, their metabolic rate is low and, under appropriate storage conditions, their dormancy can be prolonged. The biochemistry of these storage organs is geared to a slow metabolic rate designed to provide the low levels of energy required to maintain life in the cells of these tissues during dormancy.

Biochemistry of respiration

All living organisms, including fruit and vegetables, require a continuous supply of energy. This energy enables the organism to carry out the necessary metabolic reactions to maintain cellular organisation, to transport metabolites around the tissue and to maintain membrane permeability. In addition, a continuous supply of the organic molecules is required for synthetic reactions in cells.

Aerobic metabolism

Most of the energy required by horticultural produce is supplied by aerobic respiration, which involves the oxidative breakdown of certain organic substances stored in the tissues. Conventionally, a common substrate for respiration is glucose ($C_6H_{12}O_6$), and if it is completely oxidised, the overall reaction is:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

Respiration is essentially the reverse of photosynthesis – by which energy derived from the sun is stored as chemical energy, mainly in storage carbohydrates such as starch and sucrose. There are basically four processes (shown in much simplified form in Figure 3.6) involved in aerobic respiration:

1 Conversion of carbohydrate to six-carbon sugar phosphates of glucose or fructose by addition of inorganic

phosphate. These hexose phosphates are the true initial substrates for respiration via glycolysis, although glucose is often stated for convenience.

2 Glycolysis, which splits the hexose phosphates to two molecules of 3-C pyruvate, each of which is converted to 2-C acetyl-Coenzyme A. The total energy produced by conversion of one glucose molecule to two molecules of pyruvate is captured in eight ATP molecules. The process occurs in the cytoplasm.

3 The tricarboxylic acid (TCA) cycle (also known as the citric acid or Krebs cycle), which takes place in the mitochondria and oxidises acetyl-CoA to carbon dioxide and water. The acetyl-CoA combines with a 4-C organic acid to give a 6-C organic acid and then undergoes a series of reactions to 5-C and 4-C organic acids to give the original 4-C acid for the next round of the cycle. The two molecules of pyruvate give 30 ATP molecules, in addition to the eight ATP molecules from the glycolytic process.

4 The electron transport chain, located on the inner membranes of the mitochondria, is a series of dehydrogenase enzymes, cytochrome proteins, ubiquinones and other compounds which transfer electrons from NADH and $FADH_2$, produced in the reactions of glycolysis and the TCA cycle, resulting in the synthesis of ATP and regeneration of the oxidised forms of NAD and FAD for reuse in the respiratory reactions. This oxidative process requires molecular oxygen from the atmosphere and also produces water.

The production of carbon dioxide and uptake of oxygen by these metabolic processes enable the rate of aerobic respiration to be measured physiologically in plant tissues (Chapter 10).

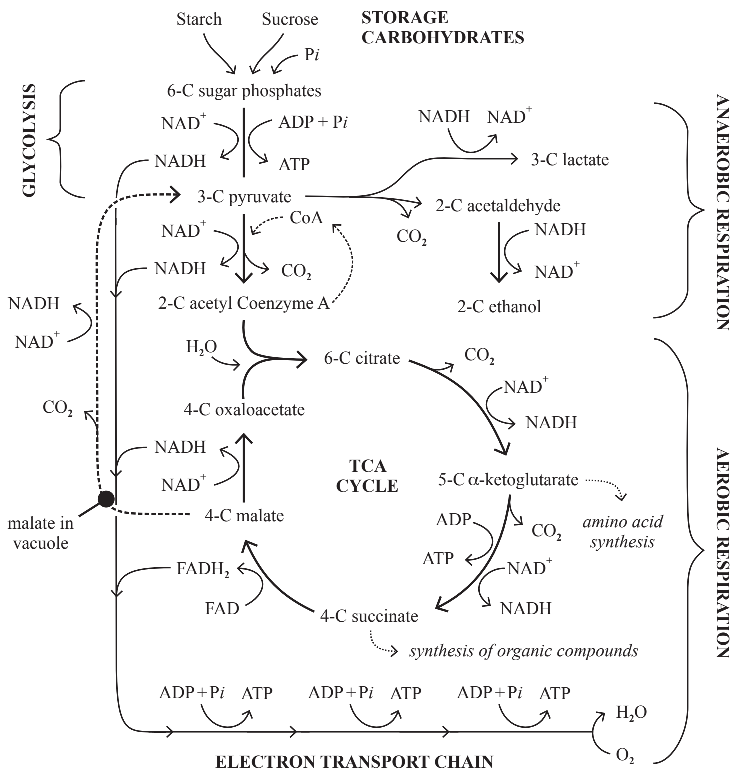


Figure 3.6 Simplified diagram of the biochemistry of anaerobic and aerobic respiration in plants. Storage carbohydrate is converted to hexose phosphate and then glycolysis produces acetyl Coenzyme A, which enters the mitochondrial TCA cycle for oxidation to carbon dioxide and water, involving the electron transport chain. Energy is stored in ATP and in reduced cofactors NAD+ or FAD. Oxygen is required.

ATP is the energy currency of cells, with the energy generated during glycolysis and the TCA cycle trapped and stored in the third phosphate bond of ATP. Since oxygen is required, the process is termed oxidative phosphorylation. The energy is subsequently made available to the plant by breaking this phosphate bond in the reverse reaction:

$$ATP \rightarrow ADP + P_i + energy$$

This energy can be used in various synthetic and other metabolic reactions in the plant cells. The total chemical energy liberated during the oxidation of 1 mole of glucose is approximately 1.6 megajoules. While most of this energy is preserved within the plant system, the remainder is lost as heat. The heat generated in respiration is a major reason for the need for refrigeration during prolonged storage.

Other respiratory pathways

The oxidative pentose phosphate pathway (OPPP) converts glucose-6-phosphate to fructose-6-phosphate and glyceraldehyde-3-phosphate and carbon dioxide through a complex cyclic reaction pathway involving 4-, 5-, 6-, and 7-carbon sugar phosphates. Although it is not considered to be a major respiratory pathway in fruits, the OPPP does provide ribose-5-phosphate for nucleotide and nucleic acid synthesis, erythrose-4-phosphate for shikimic acid and aromatic amino acid biosynthesis and $NADPH_2$ to drive a variety of synthetic reactions. The OPPP is of greater importance in leafy vegetables, in which it can account for a significant proportion of tissue respiration, perhaps in the range of 10–20%.

The vacuoles of many fruit and vegetables contain high concentrations of organic acids, particularly malic and citric acids, which can be used as respiratory substrates. These acids can be utilised directly by the TCA cycle in the mitochondria. Malic acid can also undergo reductive decarboxylation with the evolution of carbon dioxide and production of $NADPH_2$ or $NADH_2$ and pyruvate by malic enzymes present in the cytosol or in the mitochondria.

The complete oxidation of malate:

$$C_4H_6O_5 + 3O_2 \rightarrow 4CO_2 + 3H_2O$$

generates more carbon dioxide than the amount of oxygen consumed, whereas oxidation of glucose generates an equal amount of carbon dioxide for the oxygen consumed. This relationship becomes important when measuring respiration by gas exchange, in which the carbon dioxide evolved and/or oxygen consumed is measured. It is therefore possible to record different values for respiration depending on which gas is monitored. Ideally, both gases should be measured simultaneously.

Anaerobic metabolism (fermentation)

Aerobic respiratory pathways are the preferred pathways as oxygen is generally in unlimited supply. However, under various storage conditions the amount of oxygen in the atmosphere may be limited and insufficient to maintain full aerobic metabolism. Under these conditions the tissue can initiate anaerobic respiration, by which glucose is converted to pyruvate by the glycolytic pathway. But then the pyruvate is metabolised into either lactic acid or acetaldehyde and ethanol in a process termed fermentation (Figure 3.6). The oxygen concentration at which anaerobic respiration starts, known as the extinction point, varies between tissues and is usually below 1% v/v. The oxygen concentration at this point depends on several factors, such as species, cultivar, maturity and temperature, which affect the diffusion of gas to the cells. Anaerobic respiration produces much less energy per mole of glucose metabolised than aerobic pathways, but it does allow some energy to be made available to the tissue under adverse conditions. However, off-flavours, including ethanol and acetaldehyde, can result from fermentation.

Metabolites for synthetic reactions

The respiratory pathways are not only used for the production of energy for the tissue. The carbon skeletons generated during respiration are required for many synthetic reactions in the cell, and can be removed from the TCA cycle at several points. For example, 5-C α-ketoglutarate may be converted to the amino acid glutamate from which several other amino acids may be produced for protein synthesis; 4-C succinate may be diverted into the synthesis of various heme pigments including chlorophyll. The loss of α-ketoglutarate and succinate from the TCA cycle for synthetic reactions would eventually lead to cessation of the cycle. Therefore, C4 acids are fed into the cycle; they are produced principally by the fixation of carbon dioxide into phosphoenolpyruvate to give 4-C oxaloacetate. Alternatively, vacuolar reserves of malate may be utilised.

Ethylene biosynthesis and action

Ethylene is the key ripening hormone. A summary overview of the biosynthesis and action of ethylene is shown in Figure 3.7. Ethylene is produced from methionine via a pathway that includes the intermediates S-adenosyl-methionine (SAM) and 1-aminocyclopropane-1-carboxylic acid (ACC). The conversion of SAM to ACC by the enzyme ACC synthase (ACS) is thought

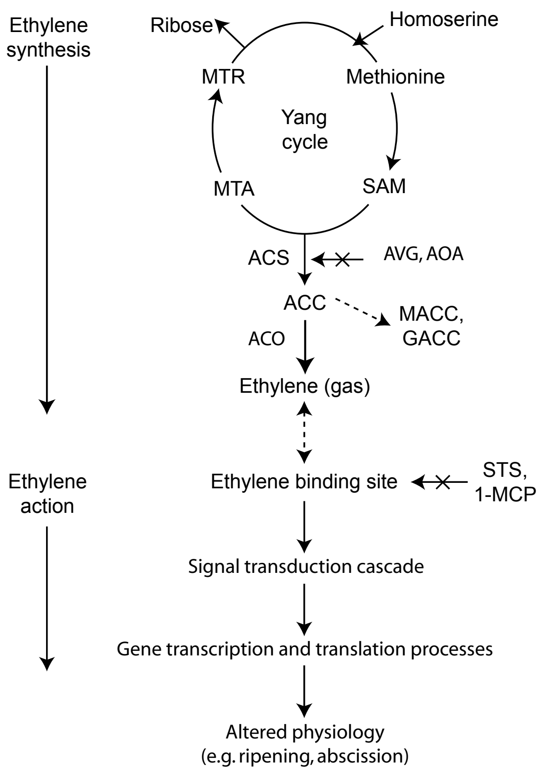


Figure 3.7 Reaction sequences in the metabolism of ethylene and its action

to be the rate limiting step in the biosynthesis of ethylene. This enzyme is located in the cytoplasm. In higher plants, ACC can be removed by conjugation to form malonyl ACC or glutamyl ACC. Addition of ACC to preclimacteric (unripe) fruit generally results in only a small increase in ethylene evolution, showing that another enzyme – ACC oxidase (ACO) – is required to convert ACC to ethylene. ACC oxidase is a labile enzyme, sensitive to oxygen. It is thought to be attached to the outer face of the plasmalemma. Factors that affect the activity of ACC synthase include the timing of fruit ripening, senescence, physical injuries and chilling injury. This enzyme is strongly inhibited by aminooxyacetic acid (AOA), rhizobitoxine and its analogue and L-2-amino-4-(2-aminoethoxy)-trans-3-butenoic acid (AVG), which are known inhibitors of pyridoxal phosphate-dependent enzymes. ACC oxidase is also inhibited by anaerobiosis, temperatures above 35°C and cobalt ions.

Mode of action

Ethylene is a plant hormone that acts with other plant hormones, such as auxins, gibberellins, cytokinins, abscisic acid and jasmonates, to exercise control over the fruit ripening process. Most of what is known about the relation of ethylene to fruit ripening is because of the availability of the sensitive gas chromatographic method for the measurement of ethylene that has enabled detailed studies of this relationship. The relationship of the other plant hormones to ripening has not been clearly defined.

It is thought that two systems exist for the regulation of ethylene biosynthesis. System 1 refers to the low levels of ethylene production in immature developing fruit and vegetative tissues. The factors controlling System 1 are unknown, but different forms of ACC synthase (ACS) and ACC oxidase (ACO) are thought to be involved compared to System 2. Once climacteric fruit reach a particular developmental stage there is a transition to System 2, which is responsible for the production of the large amounts of ethylene necessary for the full integration of ripening. System 2 is an autocatalytic process whereby the already produced ethylene triggers further production. Non-climacteric fruits and vegetative tissues do not have an active System 2. The treatment of developing climacteric fruits with ethylene can induce System 2 and premature ripening, but such fruits have poor eating quality.

Plant hormones affect plant regulation and development by binding to specific receptors in the plant or fruit. This initiates a flow of events leading to visible responses. The receptor to ethylene is in an active state in the absence of ethylene and allows normal growth in plants and fruit to continue. When ethylene is produced naturally during ripening, following a physical stress or artificially applied, it binds to the receptor and switches it off leading to a series of events such as ripening or healing of injuries in some plant organs. Ethylene action can be affected by altering the amount of receptors or by interfering with the binding of ethylene to its receptor. Binding of ethylene takes place reversibly at a site containing the transition metal cofactor copper. The affinity of the receptor for ethylene is increased by the presence of oxygen and decreased by carbon dioxide. The need for specific structural requirements for ethylene action has been demonstrated by treating tissues with analogues and antagonists of ethylene. The gaseous cyclic olefine, 1-methylcyclopropene (1-MCP) is a highly effective inhibitor of ethylene action. 1-MCP irreversibly binds to the ethylene receptors in sensitive plant tissues, and a single treatment with low concentrations for a few hours at ambient temperatures confers protection against ethylene for some time (see Chapter 6).

The pattern of changes in ethylene production rates and the internal concentrations of ethylene in relation to the onset of ripening have been observed in several climacteric fruits. In one type of fruit, ethylene concentration rises before the onset of ripening, determined as the initial respiratory increase (e.g. tomato and honeydew melon). In the second type of fruit (e.g. apple and mango), ethylene does not rise before the increase in respiration. Treatments which prevent ethylene from reaching a triggering concentration will delay ripening.

It is well known that many fruits as they develop and mature become more sensitive to ethylene. For some time after anthesis (flowering), young fruit can have high rates of ethylene production. Early in the life of fruit the concentration of applied ethylene required to initiate ripening is high and the length of time to ripen is prolonged but decreases as the fruit matures (Table 3.3). The tomato is an extreme case of tolerance to ethylene. In contrast, banana and melons can be readily ripened with ethylene even when immature. Little is known about the factor(s) that control the sensitivity of the tissue to ethylene.

Ripening has long been considered to be a process of senescence due to a breaking down of the cellular integrity of the tissue. However, ripening is now considered a genetically programmed phase in the development of plant tissue with altered nucleic acid and protein synthesis occurring at the commencement of the respiratory climacteric resulting in new or enhanced biochemical reactions operating in a coordinated manner. Both

Table 3.3 Effect of maturity on the time to ripen for tomatoes

Maturity at harvest (days after anthesis)	Days to ripen	
	Treated with ethylene	Control
17	11	_*
25	6	_
31	5	15
35	4	9
42	1	3

* Failed to ripen when experiment was terminated.
Note: Time to ripen was days between anthesis and first detectable red colour (first colour stage). Fruit were treated continuously with 1000 μL/L ethylene.

SOURCE J.M. Lyons and H.K. Pratt (1964) 'Effect of stage of maturity and ethylene treatment on respiration and ripening of tomato fruits', *Proceedings of the American Society of Horticultural Science* 84: 491–500. (Used with permission.)

views fit with the known degradative and synthetic capacities of fruit during ripening.

An additional development over the last 30 years has been identification of signalling compounds such as jasmonates, polyamines and previously considered toxic gases, nitric oxide and hydrogen sulphide. These compounds have been implicated in the regulation of ethylene synthesis and action, and further research should provide a greater understanding of ethylene metabolism and may possibly identify new postharvest treatments to manage quality.

Genetic control of ripening

Manipulation of plant metabolism to extend postharvest life has traditionally been achieved through alteration of environmental factors such as temperature or application of chemicals that enhance or inhibit some aspect of metabolism. However, with the increasing sophistication of molecular biology techniques it is now possible to alter plant metabolism at the genetic level.

It is well known that climacteric fruits show a marked increase in protein synthesis and nucleic acids (especially mRNA) synthesis preceding, and in the early stages of, the climacteric rise in respiration. There is an initial increase in certain proteins already present in unripe fruit, but later in ripening new types of proteins are synthesised. Similarly, mRNAs increase during ripening, and *in vitro* translation of these mRNAs can be shown to produce the new proteins. Many of the genes associated with the transition from the preclimacteric to climacteric stages of ripening have now been identified.

The availability of natural mutants of tomato and variants produced by genetic transformation (transgenics), which exhibit abnormal ripening behaviour, have provided valuable

Table 3.4 Mutants of tomato with abnormal ripening behaviour

Mutant	Location on chromosome	Fruit phenotype compared to wild type
Ripening inhibitor (rin)	5	Slowly turns pale yellow; very low ethylene production and PG activity; little softening; does not ripen after exposure to ethylene
Never ripe (Nr)	9	Slowly turns orange-red; limited softening, ethylene production, PG and lycopene synthesis
Non-ripening (nor)	10	More extreme than rin; final colour deep yellow; very low ethylene production; contains <1% of wild type PG

SOURCE Adapted from G. Hobson and D. Grierson (1993) 'Tomato', in G.B. Seymour, J.E. Taylor and G.A. Tucker (eds), *Biochemistry of fruit ripening*, Chapman & Hall, London: 405–42.

experimental subjects for studying the genetic regulation of ripening. Some non-ripening or slow ripening mutants affect the processes of ethylene synthesis, ethylene perception and/or signal transduction leading to abnormal colouring (often yellow or pale red), do not soften or have low ethylene production (see Table 3.4). These mutants have been extensively used to determine some of the fundamental processes involved in ripening. For example, during tomato ripening, expression of two genes, *LeACS2* and *LeACS4*, is greatly increased, which indicates ACS transcription is a major control point of ripening. In addition, seven ethylene receptor genes (*LeETR1, LeETR2, NR, LeETR4, LeETR5, LeETR6*, and *LeETR7*) have been identified, with most associated with the binding of ethylene to the enzyme receptor.

Understanding the control steps that regulate tissue softening during ripening is more complex. There are a number of hydrolase enzymes which break down the carbohydrate polymers (e.g. pectins, celluloses, hemicelluloses) responsible for the structural integrity of cell walls. Among these is polygalacturonase (PG), which hydrolyses the α(1-4) linkage between galacturonic acid residues in pectins. Early research with the tomato mutants suggested this could be the primary enzyme responsible for softening, but it is now known that a range of other proteins, including expansins, pectic lyases and β-galactosidases as well as hydrolases, lead to the wide array of changes in texture that occur during ripening and senescence. In addition, there is a well-characterised cooperative relation between PG and pectin methylesterase. De-esterification of pectins is required before PG can catalyse depolymerisation of pectin chains. Substantial alteration to fruit texture patterns requires the simultaneous modulation of multiple genes. Indeed, more than 50 genes showing differential expression during tomato fruit development and ripening encode proteins involved in the modification of cell wall architecture.

The use of mutant cultivars or genetic manipulation to develop transgenic plants in which particular enzymes (gene products) can be either virtually eliminated or enhanced was seen as an exciting prospect to achieve better quality and a longer shelf life. A notable example of this early optimism was development of the FLAVR SAVR™ tomato. This was based on reducing the activity of the enzyme endopolygalacturonase, which is involved in cell wall breakdown during ripening. This transgenic tomato remained firmer longer during ripening so that it could be kept on the plant longer before picking, with the object of enhancing flavour. However, the commercial production and marketing of FLAVR SAVR™ was short-lived.

In addition to consumer concerns with genetic manipulation, the application of genetic technologies as solutions to postharvest issues needs to be approached with some caution since plant metabolism is very adaptable due to the fact that there are usually alternate pathways by which a given metabolic product or intermediary metabolite is produced. This plasticity of metabolism will make the task of the genetic engineer more difficult.

4
Temperature

Temperature is the single most important factor determining the maintenance of postharvest quality in fruit and vegetables. Temperature responses of harvested horticultural produce can be generally classed as:

- beneficial low temperature effects
- adverse low temperature effects
- adverse high temperature effects (Figure 4.1).

In the case of adverse low temperature effects, clear mechanistic distinctions between freezing and chilling injuries can be made. Specific disorders and further details on the nature of low and high temperature effects are given in Chapters 8 and 11, respectively.

Beneficial low temperature effects

Harvested produce is ideally stored and transported under reduced temperatures likely to maximise quality and longevity. However, the effect of lowering the storage temperature on produce quality is not uniform over the normal temperature range (0–30°C for non-chilling-sensitive produce, 7.5–30°C for moderately chilling-sensitive produce, and 13–30°C for

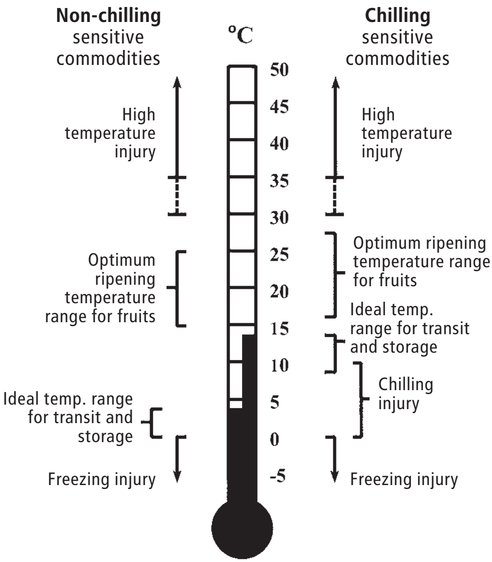


Figure 4.1 Responses of non-chilling-sensitive and chilling-sensitive produce to temperature

chilling-sensitive produce). Only a small improvement in storage life is achieved by small reductions in temperature at the upper end of the temperature range. In contrast, much larger improvements are obtained by similarly small reductions at lower temperatures (Figure 4.2), where even a change in temperature of 1°C can have a significant effect on out-turn. Ideally, the greatest reduction in processes associated with deterioration (e.g. respiration, change in texture, loss of vitamin C) and therefore best quality maintenance will be obtained if the produce is held just above its freezing point temperature or just above its chilling threshold temperature in the case of chilling-sensitive produce.

Metabolism (e.g. respiration) in fruit and vegetables involves many enzymatic reactions, and the rate of these reactions, within the physiological temperature range, generally increases exponentially with increase in temperature. This

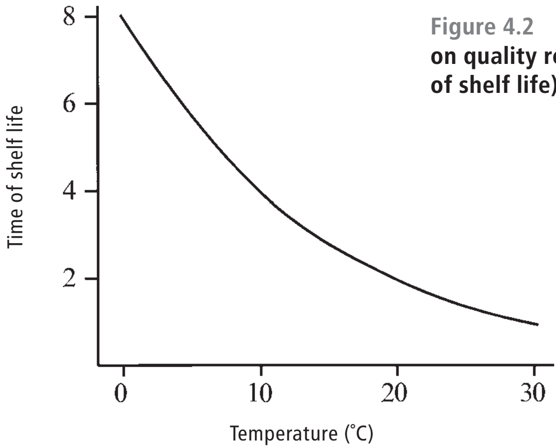


Figure 4.2 Effect of temperature on quality retention (i.e. length of shelf life)

relationship has been described mathematically by use of the temperature quotient or Q_{10}. Jacobus Van't Hoff (a Dutch chemist and the first winner of the Nobel Prize in Chemistry) determined that the rate of a chemical reaction approximately doubles for each 10°C rise in temperature. However, this relationship is of limited use as the Q_{10} for many biological processes does not remain constant over the physiological range; for example, the Q_{10} for respiration can have a value of between 2 and 8 across the physiological temperature range.

Lowering the temperature of both climacteric and non-climacteric produce lowers their rate of deterioration. However, in the case of climacteric fruit, low temperature can also be used to achieve a delay in the onset of ripening. The effect of decreased temperature on ripening follows an exponential relationship similar to that shown in Figure 4.2. Lowering the temperature not only reduces production of ethylene but also reduces the rate of response of the tissues to ethylene. Thus, at lower temperatures, longer exposures to a given concentration of ethylene are required to initiate ripening or enhance senescence.

Normal ripening occurs only within a particular range of temperature (commonly 10–30°C); although some fruit, such as some pear cultivars, will ripen slowly but satisfactorily at temperatures below 10°C. The best quality in fruit generally develops at a ripening temperature of 20–23°C.

Provided that a fruit is not sensitive to chilling, the maximum storage life can be achieved at temperatures below the ripening range. For example, Williams' Bon Chretien (or Bartlett) pears will not ripen at temperatures below about 12°C, and maximum storage life is obtained by storage at –1°C followed by removal to temperatures greater than 12°C when ripening is desired. However, if the pears are held too long at low, non-ripening temperatures, they will fail to ripen normally after removal to ripening temperatures.

For chilling-sensitive produce (such as banana and mango), the best retention of quality during storage is obtained by storing the produce just above the chilling threshold temperature. This is compared to storage and handling at just above the freezing temperature for non-chilling-sensitive produce. In addition to delaying fruit ripening and senescence processes, these basic principles of temperature management can be applied to inhibit a range of development processes in fresh produce; for example, toughening of asparagus and loss of sweetness in peas.

Adverse low temperature effects

Horticultural produce may be exposed to undesirably low temperatures due to unprotected transport in cold climatic regions, incorrect thermostat setting in storage rooms, and inappropriate location within a cool room. Freezing injury occurs at temperatures of 0°C or below and involves inter- and/or intracellular ice formation. The precise temperature at which freezing occurs depends upon the concentration of solutes (such as sugars) in the tissue, with freezing point being lowered further with increasing osmotic concentration (i.e. freezing point depression). For example, lettuce freezes at just below 0°C (about –0.2°C), while mature grape berries, which have a very high sugar content (about 14% of fresh weight), do not freeze until less than –2.0°C.

Freezing of tissue water initiates desiccation and osmotic stress of cellular structures (e.g. membranes) and constituents (e.g. proteins) because solvent water is lost to support ice crystal growth. In addition, expansion of the water upon freezing, especially intracellular ice formation, can cause considerable physical disruption to cell structure. Furthermore, upon thawing the affected tissue usually cannot resume normal metabolism or regain normal texture, therefore adversely affected freeze-thawed tissue is flaccid and/or appears water soaked. However, some produce such as cabbage, onions and some pear cultivars may be thawed without detriment. This regaining of normal form and function can be achieved if ice crystal damage is minimal and if the rate of temperature rise is sufficiently slow to allow orderly redistribution of water and reformation of intracellular compartmentation.

Chilling injury of susceptible commodities occurs at low temperatures, which are above the freezing point of the produce. Chilling injury is the result of imbalanced metabolism and loss of cellular compartmentation at sub-optimal temperatures. Factors influencing susceptibility to chilling injury are discussed in Chapter 8, as are the myriad chilling injury symptoms. Subtropical and tropical commodities are especially chilling sensitive, with chilling thresholds for tropical produce commonly around 13°C.

Manifestation of chilling injury is a function of time by temperature. Thus, a short period at a certain temperature below the chilling threshold temperature may not result in the development of chilling injury symptoms in a specific produce. However, relatively longer exposure times will result in irreversible damage, with the extent of injury increasing with increasing duration. Conversely, the development of chilling injury symptoms will be more severe in chilling susceptible produce held for a shorter period well below the chilling threshold temperature.

Microbial and insect pest activities are considered in Chapters 9 and 11, respectively, but it is important to note that good temperature management can greatly diminish the rates of pathogens and pests. For example, microbial growth is often only the visible symptom of wastage whose primary cause is poor temperature management, for example with strawberries. Bacterial and fungal organisms exploit the tissue deterioration (e.g. leakage of cellular contents) associated with adversely low or high temperatures or simply with ongoing ripening and senescence processes in the normal physiological temperature range. Similarly, the rate of pest insect development within produce can be slowed at low temperatures. Indeed, cold treatment is widely used as a postharvest disinfestation procedure in various crops (Chapter 11). Accordingly, there is an obvious role for optimising temperature management to minimise reliance on chemical control measures.

Adverse high temperature effects

Many tropical fruit and vegetables are more tolerant of high temperatures, and they are adapted and grow in high temperatures. However, unusually high temperatures are associated with 'assaults' such as exposure of harvested produce to direct sunlight, hot ambient air and heat treatments for pest eradication (e.g. hot water dips). The activity of enzymes in fruit and vegetables generally declines at temperatures above 30°C. At certain temperatures, specific enzymes become inactive (denature); many are still active at 35°C, but most are inactivated at 40°C.

Continuous exposure of some climacteric fruit to temperatures around 30°C allows the flesh to ripen but inhibits fruit colouration. For example, the peel of Cavendish bananas (cultivars Valery and Williams) remains green, while in tomatoes lycopene (red pigment) accumulation is inhibited during ripening at elevated temperatures. When produce is held above 35°C, its metabolism becomes abnormal and this leads to a breakdown of membrane integrity and structure, resulting in the disruption of cellular organisation and rapid deterioration of the produce. These changes are often characterised by a general loss of pigments, and the tissues may develop a watery or translucent appearance. This condition in banana and tomato is often referred to as 'boiled'.

Sugar–starch balance

The storage of some vegetables (including potato, sweet potato, green peas and sweet corn) at low temperatures can alter the starch–sugar balance in the produce. At any temperature, starch and sugar are in dynamic equilibrium and some sugar is degraded to carbon dioxide during respiration:

$$\text{starch} \longleftrightarrow \text{sugar} \rightarrow CO_2$$

At ambient temperatures, the starch–sugar balance in potato and sweet potato is heavily biased towards accumulation of starch. When these vegetables are stored at lower temperatures, the rate of respiration and the conversion of sugar to starch decreases. The critical temperature at which accumulation of sugar commences depends on the commodity; for example, it is about 10°C for potato and about 15°C for sweet potato. The accumulation of sugar is profoundly undesirable in many starchy vegetables. Potato with a high sugar content has poor texture and a sweet taste when boiled. When these potatoes are fried, excessive browning occurs due to caramelisation and reactions between amino acids and sugars (Maillard reaction) and this is commercially unacceptable. The accumulation of sugar in potato stored at low temperatures can be largely reversed by raising the storage temperature to 10°C or above. Although it is widely accepted that the sugar level returns to nearly normal during one week at 15–20°C, experience has shown that the decrease in sugar level may occur at a much slower rate, especially after prolonged storage at low temperatures. In other vegetables, such as sweet corn and peas, a high sugar content is desired. These vegetables are harvested immature when the sugar content is highest, and rapid storage at quite low temperatures is necessary to retard conversion of sugar to starch.

Storage life

There is no one ideal temperature for the storage of all horticultural commodities, as their responses to temperature vary widely. Important physical processes such as transpiration and physiological reactions like chilling injury must be taken into account, as must the required duration of storage. For fruit and vegetables not susceptible to chilling injury, the maximum storage life can be obtained at temperatures close to but above the freezing point of the tissue. For chilling-sensitive produce, there are also potential immediate advantages of applying low temperature during storage and distribution. Recommended storage conditions are therefore a compromise to obtain the maximum time without any adverse reaction to the imposed environmental conditions.

General storage temperature ranges recommended for a selection of fruit and vegetables are presented in Table 4.1. The storage period ranges listed under each of the three storage temperature ranges recognise that for a particular produce, factors such as cultivar, season and maturity at harvest can give different physiological and metabolic responses which result in variations in the optimum storage temperature. Moreover, the optimum storage temperature can be slightly outside the ranges specified in Table 4.1. For instance, optimum storage temperatures reported for apples range from –1°C to 5°C. The temperature groupings in Table 4.1 also have application when the volume of specific produce lines being handled is insufficient to fill a storage room or transport container. Thus, a number of different types of produce often need to be held in the same storage chamber and so temperature compromise is required. Generally, safe temperature settings for long-term mixed storage of horticultural produce could be 1°C for produce that is not susceptible to low temperature injury, 5°C for produce that is susceptible to low temperature disorders and 10°C for produce that is susceptible to chilling injury. Considerations of compatibility of humidity requirements (see Chapter 5) and for ethylene sensitivity (see Chapter 6) are also important in determining the feasibility of mixed storage arrangements.

Table 4.1 Recommended temperature to maximise storage life of selected fruit and vegetables

	Time at optimum temperature (weeks)		
Produce	**–1–4°C**	**5–9°C**	**10°C+**
FRUIT			
Very perishable (0–4 weeks)			
Apricot	2		
Banana, green			1–2
Berry fruits (except blueberries)	1–2		
Cherry	1–4		
Fig	2–3		
Mango			2–3
Strawberry	5 days		
Watermelon		2–3	
Perishable (4–8 weeks)			
Avocado		3–5	
Grape	4–6		
Mandarin		4–6	
Passionfruit		4–5	
Peach	2–6		
Pineapple, green			4–5
Plum	2–7		
Semi-perishable (6–12 weeks)			
Coconut	8–12		
Orange		6–12	
Non-perishable (>12 weeks)			
Apple	8–30		
Grapefruit			12–16
Pear	8–30		

	Time at optimum temperature (weeks)		
Produce	**–1–4°C**	**5–9°C**	**10°C+**
VEGETABLES			
Very perishable (0–4 weeks)			
Asparagus	2–4		
Bean	1–3		
Broccoli	1–2		
Cucumber		2–4	
Lettuce	1–3		
Mushroom	2–3		
Pea	1–3		
Tomato			1–3
Perishable (4–8 weeks)			
Cabbage	4–8		
Semi-perishable (6–12 weeks)			
Celery	6–10		
Leek	8–12		
Marrow			6–10
Non-perishable (>12 weeks)			
Carrot	12–20		
Onion	12–28		
Potato		16–24	
Pumpkin			12–24
Sweet potato			16–24

When consulting published tables of recommended storage conditions, it is important to remember that such tables have been compiled from data generated by many research groups in many countries. They should therefore only be accepted as a guide to likely storage behaviour for any particular commodity. The precise optimal storage conditions for a specific variety of a particular commodity grown in a specific locality need to be determined experimentally.

The storage times presented for various produce in Table 4.1 show a wide variation ranging from a few days to many months. While the storage life of individual produce is governed by many factors, an overriding determinant as to whether it has a short or long storage life is the overall rate of metabolism, which is related to the respiration rate. Produce with a low respiration rate generally store for longer periods. Some examples of produce respiration rates are given in Table 4.2. Produce

Table 4.2 Typical respiration rates of selected fruit and vegetables

Fruit	Respiration rate at 15°C (mL CO_2/kg/h)	Vegetable	Respiration rate at 15°C (mL CO_2/kg/h)
Apple	25	Bean	250
Banana, green	45	Cabbage	32
Banana, ripe	200	Carrot	45
Grape	16	Lettuce	200
Orange	20	Pea	260
Peach	50	Potato	8
Pear	70		
Strawberry	75		

SOURCE Adapted from American Society of Heating, Refrigerating, and Air-Conditioning Engineers (1986) *ASHRAE handbook of refrigeration systems and applications*, ASHRAE, Atlanta GA.

which have the shortest storage life are leafy vegetables, fruits that are harvested when ripe and rapidly metabolising (e.g. berries) and chilling-sensitive tropical fruit that cannot be held at low temperatures to decrease their metabolic rate. Produce with the longest storage life are generally underground vegetables and those pome and citrus fruits which have a relatively low respiration rate and/or can tolerate low temperature storage.

Temperature recommendations for different commodities

Leafy vegetables and immature flower heads

Many of these vegetables comprise immature tissues, which have very high rates of respiration. They should be cooled to about 1°C as soon as practical after harvest and maintained at low temperature throughout storage and preferably also during marketing. Some consideration needs to be given to removal of the heat of respiration from more immature vegetables, which may require ventilation with high humidity air.

Vegetable fruits

Vegetable fruits can be divided into two sub-groups: those consumed in an immature unripe condition (e.g. green legumes, cucumbers and peppers) and those consumed when mature and ripe (e.g. melons, pumpkins and tomatoes). Most vegetable fruits are to some extent susceptible to low temperature injuries and are therefore stored at temperatures ranging from 3–5°C for beans to 10–15°C for pumpkins. There are exceptions, such as green peas, which can be stored at 0°C. Tomatoes, as with many other climacteric fruits, are more tolerant of low temperature when ripe.

Underground vegetables

This group encompasses diverse organ types, including bulbs (e.g. onion), roots (e.g. carrot), tubers (e.g. potato) and rhizomes (e.g. ginger). Most underground organs are characterised by a low respiration rate and thus tend to have a relatively long storage life. Bulbs can be stored at 0°C or slightly lower. They should not be held for extended periods at 5–20°C as rotting and sprouting occur rapidly at these temperatures. It is recommended to store most temperate root vegetables at 0°C. Sweet potato, which is a fleshy storage root, is susceptible to chilling injury at temperatures below 10°C. Most tubers are susceptible to low temperature injuries and should be held at temperatures ranging from 5–15°C. Sprouting and rotting are the major storage problems.

Deciduous tree and vine fruit

The storage life of deciduous fruit tree products is highly variable, ranging from one to two weeks for apricots and figs to over six months for some apples and pears. Temperate fruits with an inherently short storage life benefit from rapid cooling after harvest. The recommended storage temperature for most deciduous and vine fruit is –1 to 0°C. The exceptions are specific apple and pear cultivars that are susceptible to physiological disorders, where the recommended temperature can be up to 5°C. While deciduous fruit with a relatively short storage life are also generally susceptible to low temperature injuries, 0°C remains the recommended temperature as an even shorter storage life through enhanced senescence occurs at slightly higher temperatures. For example, peaches can develop chilling injury (mealiness) at 5°C. Care must be taken with unripe deciduous fruit as prolonged storage at low temperature can inhibit the ability of fruit to ripen after cool storage.

Berries

As a group, berries are probably the most perishable of all fruit. Some, such as blackberries, have only a few days storage life even under optimal conditions. Berries are non-climacteric fruit with high respiration rates and so are harvested at optimum eating quality. Their soft and succulent nature renders them highly susceptible to physical damage that leads to general senescence and rotting (blueberries, however, can be stored for longer periods). The recommended storage temperature for most berries is –1 to 0°C.

Citrus fruits

Citrus fruits are prone to develop a wide range of physiological disorders. Susceptibility to these disorders varies greatly among species, between cultivars and often across growing regions (see Chapter 8). The genotype-associated variability gives rise to a wide range of recommended storage temperatures, from 4°C for mandarin to 15°C for grapefruit.

Tropical and subtropical fruits

Most tropical and subtropical fruits are susceptible to low temperature injuries, with the degree of severity often related to temperature conditions prevailing in the production environment (see Chapter 8). Most tropical fruits are highly susceptible and should not be stored below 10°C. Some subtropical fruit such as avocado have a wide range of recommended temperatures from 4–13°C. Ripe fruit can often be stored at temperatures about 5°C less than unripe fruit, albeit with a more limited storage life.

Matching postharvest technology with market need

All postharvest interventions, whether from changes in handling, storage or transport systems, come at some economic cost, which must be recouped from an improved market return. It is important not to over-capitalise in the postharvest technology if the economic return will not realised. For example, there are unnecessary costs in refrigeration energy to store produce at the optimum low temperature, if the produce is marketed well before the maximum storage life at that temperature. This is discussed further in Chapter 12.

Cooling of produce

The objective of postharvest storage is to maintain the nutritional and eating quality of the produce to reach the consumer. This is done by slowing the rates of produce deterioration without predisposing it to abnormal ripening or other undesirable changes. The low temperature storage of horticultural produce is more demanding than for other foods as, in addition to having sufficient refrigeration capacity to cool the produce to the required temperature, it is necessary to make provision for the continuous removal of the heat generated by respiration (vital heat), and maintenance of high humidity around produce. Cool stores for fresh horticultural produce are generally required to operate within relatively close temperature limits (e.g. ±1°C), both in space (i.e. throughout the room) and time (i.e. constantly), in order to maximise storage life and eating quality and to avoid freezing and minimise desiccation.

The temperature of horticultural produce at harvest is close to that of ambient air. However, if produce is in the direct sun, even if the ambient temperatures are around 25°C, the produce temperature can be over 40°C. At such temperatures, respiration rates are extremely high and postharvest life will be greatly reduced. It is often good practice to harvest early in the morning to take advantage of the lower ambient temperature. Harvesting at night has been investigated in certain situations, although the practice has not been sustained for reasons which include safety, cost and inconvenience. Early morning harvesting may not be feasible for larger growers where large volumes of produce need to be rapidly harvested, and in situations where morning temperatures in tropical areas may still be relatively high.

In general, the quicker the temperature of produce is reduced to the optimum storage temperature the longer will be its storage life. The temperature of produce in the orchard/field is called field heat. Rapid or fast cooling after harvest to remove field heat is generally referred to as 'precooling', which particularly benefits highly perishable (e.g. raspberries) and/or rapidly developing horticultural commodities (e.g. asparagus). Special facilities for fast cooling of produce after harvest are often essential because refrigerated transport spaces such as trucks and shipping containers are generally not designed either to remove field heat or have adequate cold air circulation within and/or around individual containers. Rather, transport units are designed to maintain precooled produce at the selected transport temperature. The maximum acceptable loading temperatures for perishable produce are now commonly and closely controlled in order to help ensure that produce will out-turn in good condition following refrigerated transport.

The term precooling is loosely applied such that it encompasses any cooling treatment given to produce before shipment, storage or processing. A stricter definition of precooling would include only those methods by which the produce is cooled rapidly, certainly within 24 hours of harvest. The benefits of rapid precooling as soon as possible after harvest are well understood and used by many horticultural industries.

Selection of the most appropriate precooling method depends on three main factors: the temperature of the produce at harvest, the physiology of the produce, and the desired postharvest life. Rapidly respiring commodities, which have a short postharvest life, need to be quickly cooled soon after harvest; whereas commodities that have a longer postharvest life generally do not have to be cooled quite so rapidly, but nonetheless should still be cooled as soon as possible. Commodities that are susceptible to chilling injury should be cooled according to their individual requirements. Generic temperature recommendations for non-chilling sensitive, moderately chilling sensitive and highly chilling sensitive commodity groupings are 0°C, 5–7.5°C, and 13–15°C, respectively (Table 4.1). However, produce that is to be 'cured' (Chapter 11) at temperatures above those required for extended storage are not normally precooled (e.g. potato, yam and sweet potato).

Cooling rates

The rate of cooling of produce is dependent primarily on:

- the rate of heat transfer from the produce to the cooling medium. This is influenced by the rate of flow of the cooling medium around or through the containers of produce and the extent of contact between the two

- the difference in temperature between the produce and the cooling medium
- the nature of the cooling medium
- the thermal conductivity of the produce.

When warm produce is exposed to cold air kept at a constant temperature by refrigeration, the rate of cooling is not constant, but diminishes exponentially as the temperature difference (driving force) between produce and air falls (Newton's Law) (Figure 4.3).

The 'half' and 'seven-eighths' cooling times are important concepts to understand cooling and are the times required to reduce the temperature difference between the produce and the

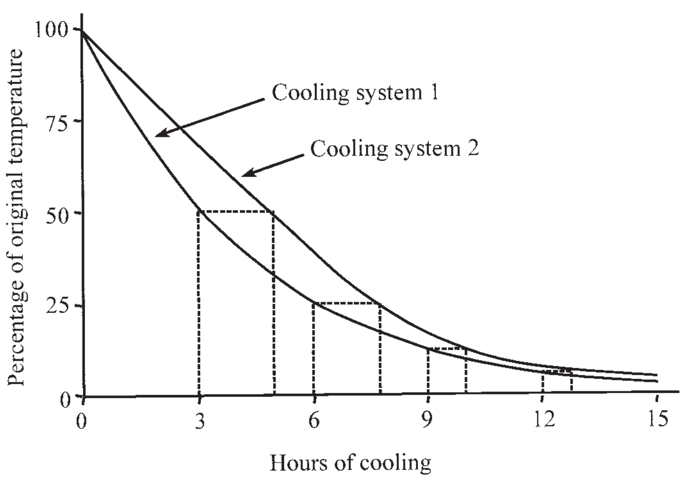


Figure 4.3 Cooling system 1 illustrates the ideal curve to achieve seven-eighths cooling (three half-cooling times, or 12.5% of the original temperature) in 9 hours. Cooling system 2 indicates the relative temperature change in the interior of a bulky commodity such as melons.

cooling medium by one-half or by seven-eighths, respectively. The seven-eighths cooling is of more practical use in commercial cooling operations, as the temperature of the produce at the seven-eighths cooling time is acceptably close to the required storage or transport temperature. In systems where the cooling rate is rapid, the temperature change in the interior of produce lags considerably behind the change in surface temperature. This is particularly true for bulky products such as melons. In such cases, the limiting factor is the rate of heat conduction to the surface of the produce. This positional lag effect can further alter the rate of cooling.

The cooling method, type of packaging, and the way the packages are stacked will all influence the rate of cooling of produce. The influence of such factors on the one-half cooling rate is shown in Table 4.3.

Table 4.3 Half-cooling times for apples

Cooling method	Z (h)
Packed in 18 kg box placed in:	
Conventional cool room	12
Air tunnel of velocity 200–400 m/min	4
Single fruit placed in air tunnel of:	
Velocity, 40 m/min	1.25
Velocity, 400 m/min	0.5
Hydrocooling of loose fruit	0.33

SOURCE E.G. Hall (1972) 'Precooling and container shipping of citrus fruits', *CSIRO Food Research Quarterly* 32: 1–10. (Used with permission.)

Methods of cooling

Produce may be cooled by means of cold air (room cooling; forced-air or pressure cooling), cold water (hydrocooling), ice and evaporation of water (evaporative cooling; vacuum cooling). Fruit are normally cooled with cold air, although cherries benefit from hydrocooling. Any one of these cooling methods may be used for vegetables depending upon the structure and physiology of the specific commodities, and upon market requirements and expectations.

Room cooling

Probably the most common cooling technique is room cooling, where produce in packages or bulk containers is exposed to cold air in a normal cool store. For adequate cooling, air needs to move around the packages, with an acceptable flow rate being 60 m/min. Produce may be cooled and stored in the same place, thereby minimising rehandling. This can be feasible if produce is supplied over time so that only small demands are placed on the room refrigeration system, which is relatively inefficient for cooling compared to specialised precooling systems. However, the significant disadvantages of room cooling are the slow rate of cooling and that it uses comparatively more space as produce must be widely spaced to maximise cooling. In addition, condensation may be a problem with room cooling, where transpired water vapour may condense on the faster cooling outermost packaging and produce (Chapter 5).

Forced-air (pressure) cooling

The rate of cooling with cold air is significantly increased if the heat transfer surface (i.e. contact area) is enlarged from that of the package to the total surface area of the produce within the package. By forcing air through packages and around each item of produce, forced-air cooling can cool produce in about one-quarter to one-tenth the time required for room cooling.

Most commonly, pressure cooling involves passing cold air down an induced pressure difference (gradient) past initially warm produce in specially vented containers (Figure 4.4). The pressure differential is induced by fans that circulate cold air through the produce and packaging, which constitute the resistance to air flow. Pressure differentials between opposite faces of packages range from barely measurable to about 250 Pa, with

Figure 4.4 **Air flow in forced-air (pressure) cooling.** Packages and containers must be vented (at least 5% of exposed surface area) and stacked so that the cooling air is forced to flow through the containers and around the produce to return to the exhaust fans. A slight pressure drop occurs across the produce as air exhausts from the space between the stacks of produce.

air-flow rates that vary between 0.1 and 2.0 L/sec.kg. Within limits, the speed of cooling can be adjusted by varying the rate of air flow. Refrigeration requirements for pressure cooling are often over-estimated because of a lack of understanding of the factors that limit the rate of heat loss from the cooling produce. Such over-estimation of refrigeration requirements increases the initial capital cost of a cooling plant unnecessarily. The thermal properties of the stacks of packaged produce should be taken into account when calculating refrigeration capacity.

Maintaining high humidity during forced-air cooling is generally not considered critical as the process is relatively rapid. However, this generalisation applies mostly to commodities with a low surface area to volume ratio such as fruit and fruit-type vegetables. High humidity pressure cooling systems (e.g. air-wash refrigeration systems) have been developed for use with commodities with a high surface area to volume ratio like leafy vegetables. Once a commodity has been adequately cooled, air velocity should be reduced or the produce transferred to a normal cool room to reduce the risk of desiccation.

Hydrocooling

Hydrocooling uses water as the heat transfer medium and therefore both produce and containers must be tolerant to getting wet. Since water has a far greater heat capacity than air, hydrocooling is comparatively rapid provided that the water contacts most of the surface of the produce and is maintained close to the prescribed temperature, usually 0°C. In many hydrocooling systems, produce passes under cold showers on a continuous feed conveyor (Figure 4.5). Alternatively, cold water baths and/or batch process systems may be utilised. A further advantage of hydrocooling is that the commodity loses little weight during

Figure 4.5
Hydrocooling unit designed to remove field heat from harvested stone fruit in bulk plastic bins. The bins travel slowly through a high-volume cold water shower. Cooling fruit from about 35°C to about 18°C takes approximately 20 minutes.

cooling. When cooling is completed, produce must be moved to a cool room to prevent re-warming. Although hydrocooling may also help clean the produce, there is a risk of contaminating produce with spoilage microorganisms if soil and rotten fruit debris are not removed (e.g. allowed to settle, or filtered) from the system, and the water renewed and/or disinfected. A contaminated hydrocooling system will infect all produce put through the system, therefore strict water sanitation should be practised.

Icing

Before the advent of comparatively modern precooling techniques, contact or package icing was used extensively for precooling produce and maintaining temperature during transit, particularly for the more perishable commodities such as leafy vegetables. The melting of ice to water (latent heat of fusion) absorbs 335 kJ (heat energy) per kg. Contact icing is now mainly employed as a supplement to other forms of precooling and transport. In top icing, finely crushed ice or an ice slurry (liquid ice: 40% water, 60% ice, 0.1% salt) is sprayed onto the top of the load of produce. In some distribution and marketing systems this practice is common but largely unnecessary, expensive (transporting frozen water) and also undesirable due to the promotion of rots. The addition of crushed ice to precooled produce, such as broccoli packed in polystyrene containers, in some markets is common but unnecessary, although it is claimed to maintain freshness during transport and marketing. In addition, food safety concerns with the use of non–food-grade water supply for ice-making may restrict its use. Therefore packing icing should be discouraged in favour of refrigerated handling and transport. Nevertheless, it is still used in some air freight situations due to difficulties in maintaining temperature control throughout the complex handling regime at airports.

Vacuum cooling

Vegetables such as lettuce, with a high surface to volume ratio, may be quickly and uniformly cooled by boiling off some of the constituent water at reduced pressure. The rate of cooling with this method is at least as rapid as that achieved with hydrocooling. In principle, vacuum cooling is evaporative cooling, exploiting the latent heat of vaporisation of water. Produce is loaded into a sealed container, and the pressure is reduced from regular atmospheric pressure (101 kPa) to about 0.66 kPa (Figure 4.6). At this sub-atmospheric pressure, water boils at 1°C, but for every 5°C drop in temperature approximately 1%

Figure 4.6 Hydro-vacuum cooler with capacity to cool four pallets of produce

SOURCE Agsell Pty Ltd, Adelaide, South Australia.

of the produce weight is lost as water vapour. This water loss can be minimised by spraying the produce with water either before placing in the vacuum chamber or towards the end of the vacuum cooling operation (hydro-vacuum cooling). The rate of vacuum cooling is largely dependent on the surface to volume ratio of the produce and on the ease with which the commodity loses water. Leafy vegetables such as lettuce are ideally suited to vacuum cooling, and other vegetables such as asparagus, broccoli, Brussels sprout, mushroom and celery can also be successfully vacuum cooled. However, fruits that have a low surface to volume ratio and/or a waxy cuticle lose water slowly and therefore do not benefit by vacuum cooling. The comparative cooling of several vegetables is shown in Table 4.4.

Table 4.4 Comparative cooling of vegetables from an initial temperature of 20°C under similar vacuum conditions

Produce	Final temperature (°C)
Lettuce, onion	2
Sweet corn	5
Broccoli	6
Asparagus, cabbage, celery, pea	7
Carrot	14
Potato, zucchini	18

SOURCE Adapted from American Society of Heating. Refrigerating and Air-conditioning Engineers (1986) *ASHRAE handbook of refrigeration systems and applications*, Atlanta, GA.

Evaporative cooling

Evaporative cooling is a simple process in which dry air is cooled by blowing it across a wet surface. The evaporation of water (latent heat of vaporisation) absorbs 2260 kJ (heat energy) per kg. The technique is efficient only under conditions of low ambient humidity (e.g. summer in Mediterranean-type climates, arid and semi-arid regions) and requires a good quality water supply. It has the advantage of low energy cost. The commodity may be cooled either by the humidified cool air, or by misting with water then blowing dry air over the wet commodity. The extent to which air may be cooled by evaporation of water is a function of the water-holding capacity of the air, which in turn is a function of temperature and relative humidity (see Chapter 5).

5
Water loss and humidity

Since fresh fruit and vegetables are mostly water (typically 80–90%), water loss from commodities has considerable commercial significance. Many kinds of produce are sold by weight, therefore water loss constitutes a direct financial loss that is not recoverable. Furthermore, a 5% weight loss will cause many perishable commodities to wilt or shrivel. This level of water loss can occur in some produce in just a few hours under warm, dry conditions. Even in the absence of physical wilting, water loss can equate to loss of quality such as reduced crispness and other undesirable changes in colour, palatability and loss of nutritional quality (Figure 5.1).

In contrast, wetting of produce can also result in substantial losses with some commodities. Free water encourages microbial decay and in some cases causes splitting of commodities (e.g. cherries). Additionally, free water can encourage undesirable growth, such as rooting and sprouting of potatoes and onions.

Definitions

Although many terms associated with water relations can appear complicated, it is necessary to appreciate these underlying concepts to manage the storage environment.

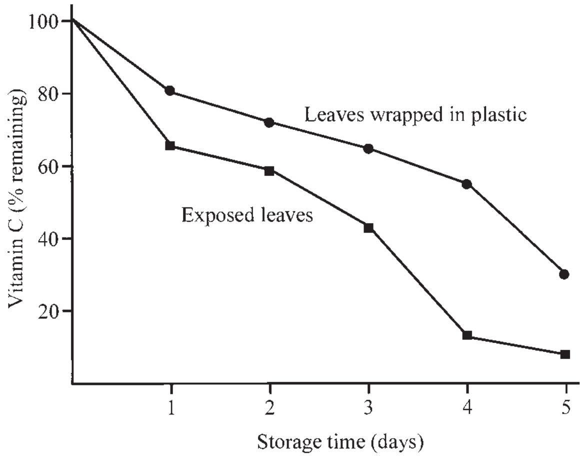


Figure 5.1 Loss of ascorbic acid (vitamin C) during storage of exposed and plastic-wrapped *Brassica juncea* leaves at 24–28°C. Initial content of vitamin C was about 18 μg/mL.

SOURCE Adapted from H. Lazan, Z.M. Ali and F. Nahar (1987) 'Water stress and quality decline during storage of tropical leafy vegetables', *Journal of Food Science* 52: 1286–88.

Water potential

In plant tissue, turgor pressure within the cells provides physical support and helps drive cell expansion. This is because water contained within the cells pushes against surrounding semi-permeable membranes and cell walls. The positive water pressure results from more water being attracted into cells than can actually be accommodated. Water is drawn into cells by their negative osmotic potential, which is due to dissolved organic (e.g. sugars) and inorganic (e.g. salts) solutes in the cell sap. Because positive turgor pressure is smaller in magnitude than negative osmotic potential, the two components balance to generate a tissue water potential that is negative.

After harvest, water loss (transpiration) in the absence of water supply could soon dehydrate plant tissue. This is because the water potential of warm, dry air is lower (more negative) than that of the plant tissue. Loss of water leads to wilting when turgor falls to zero. However, wilting may not be immediately obvious in all tissues such as those made up of thick-walled cells. Moreover, water loss from harvested produce is slowed by structural barriers (e.g. a waxy cuticle) and physiological controls (e.g. stomatal closure), which confer significant resistance to water loss in many produce.

Vapour pressure

Humidity is the general term referring to the presence of water vapour in air. If pure water is placed in an enclosure containing dry air, water molecules will enter the vapour phase until the air becomes saturated with water vapour. The pressure that these molecules exert on the container walls is the vapour pressure (VP). The amount of water vapour in atmospheric air can vary from zero to a maximum that is dependent on temperature and pressure. For example, saturated air at 30°C contains approximately 30.4 g water/m^3 of air and the VP is about 4.25 kPa.

Relative humidity

Relative humidity (RH) is the best known term for expressing the moisture content of air. RH is defined as the ratio of the water vapour pressure in the air to the saturation vapour pressure possible at the same temperature, and is expressed as a percentage (%). Saturated air therefore has a RH of 100%.

Equilibrium relative humidity

When water-containing plant tissue material is placed in an enclosure filled with air, the water content of the air increases or decreases until equilibrium relative humidity (ERH) is reached. At this point, the number of water molecules entering and leaving the vapour phase is equal. ERH is a property of the moisture content of the individual plant tissue. Pure water has an ERH of 100%.

Measures of ERH are of particular interest to microbiologists because small reductions in water activity ($a_{w,}$ which = ERH/100) and water potential equivalent to a reduction in ERH to about 95% can inhibit the growth of most bacteria and fungi in culture. However, growth of some pathogenic fungi is not prevented until water activity and water potential are reduced to less than the equivalent of about 85% ERH.

Psychrometric charts

Psychrometric charts graphically relate various properties (e.g. wet bulb and dry bulb temperatures, and water vapour pressure) of moist air to one another (Figure 5.2). The scale along the bottom axis of Figure 5.2 indicates dry bulb temperatures as given by a wet-and-dry bulb hygrometer. At all temperatures, dry air has no water and, therefore, a water vapour pressure of zero. The curved line at the top of Figure 5.2 illustrates the relationship between VP and temperature in saturated air, and is the line of 100% RH. Other curved lines can be drawn representing constant RH over a range of temperatures. The curvature of these lines shows that the VP of water increases rapidly with temperature. For example, at 30°C in saturated air (100%

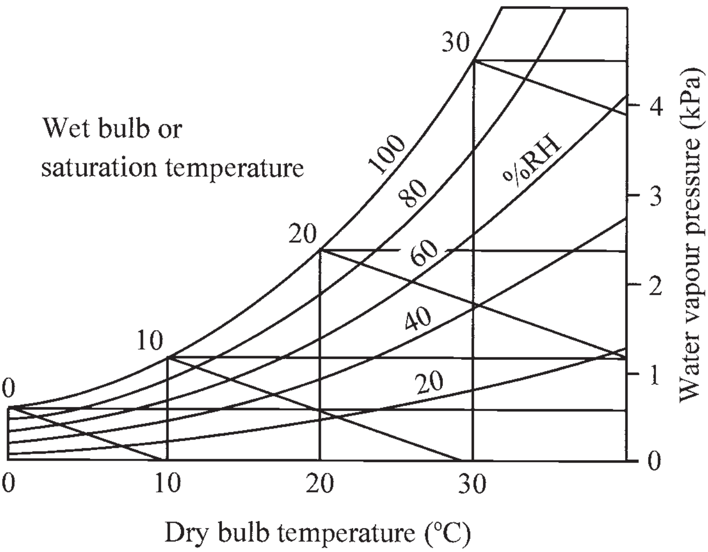


Figure 5.2 **Simplified psychrometric chart**

RH) the VP of water is 4.3 kPa; while at 20°C the VP is less at 2.4 kPa; and at 10°C it is only 1.3 kPa.

Vapour pressure deficit

The difference between the VP of the produce, which is a function of temperature and ERH, and that of the surrounding air, which is a function of temperature and RH, is called the vapour pressure deficit (VPD). VPD calculations can be used to compare relative rates of water loss under different sets of conditions. Consider, for example, produce at 20°C and 97% ERH and humidified air at 0°C and 100% RH (Scenario 1). The VP of the produce will be about 2.4 kPa, whereas that of the air will be about 0.6 kPa (Figure 5.2). Thus, the VPD will be 1.8 kPa (i.e. 2.4 kPa [produce] – 0.6 kPa [air]) and water will be lost from the produce.

Consider now the relative rate of water loss for produce already cool at 5°C (97% ERH) being placed into the same airstream (0°C, 100% RH) (Scenario 2). The VP of this produce will be 0.9 kPa (5°C, 97% RH) and the VP of the airstream will still be 0.6 kPa. Thus, the VPD for this second set of conditions will be 0.3 kPa (i.e. 0.9 kPa – 0.6 kPa). Accordingly, initial water loss under Scenario 1 is likely to occur at about six times the rate of water loss under Scenario 2 (i.e. difference between 1.8 kPa and 0.3 kPa = 6 times).

Condensation

Dew point is an important physical property of moist air that is evident in psychrometric charts. When moist air is cooled, a temperature is reached at which the VP of the air reaches the maximum for that temperature. With further cooling, water will condense. For example, fog is water condensing on a cooler surface. The temperature at which condensation occurs is the dew point temperature. The horizontal lines in Figure 5.2 can be used to find dew point temperatures. Thus, air of 80% RH at 30°C becomes saturated when cooled to about 26°C. The dew point temperature is equal to the dry bulb temperature at the point of intersection with the saturation curve. The lines which slope upwards from right to left in Figure 5.2 indicate constant wet bulb temperatures.

This has practical consequences, as for example, placing a fibreboard carton of warm transpiring produce in a cold room results in the carton cooling relatively quickly and water evaporated from the hot produce will condense onto the carton. A

Figure 5.3 Collapse of stack of cartons due to weakened carton strength caused by high humidity and water condensation

SOURCE Andrew Macnish, Queensland Department of Agriculture and Fisheries.

damp carton may collapse under the weight of other cartons, resulting in physical damage to produce. This occurs because the strength of fibreboard is substantially reduced when it is moistened. In an alternative scenario, condensation will form on cooled produce in warm moist air (e.g. in a warming carton). This can occur in humid markets in tropical areas where cartons of fruit from the cool room are placed in warm, wet markets. This free water affects the carton strength, leading to collapse of pallets of fruit (Figure 5.3). In addition, this condensation (free water) on the fruit can promote rot development, accelerate warming of the produce through the release of latent heat of vaporisation and high thermal conductivity, and induce splitting through increased turgor and interfere with respiratory and other gas exchange due to diffusion of gas in water being 10 000 times slower than in air. Even under conditions of low storage temperatures of 0°C and a high RH of 95%, extremely small fluctuations in temperature (<0.5°C) can result in condensation on cooling surfaces.

Factors affecting water loss

The physicochemical characteristics that determine inherent rates of postharvest water loss (transpiration) vary widely in different fruit and vegetables. Some examples of relative rates of water loss for a range of products are presented in Table 5.1.

Table 5.1 Transpiration coefficients for selected horticultural produce

Product	Transpiration coefficient (mg/kg.sec/MPa)	Range
Apple	42	16–100
Brussels sprout	6150	3250–9770
Cabbage	223	40–667
Carrot	1207	106–3250
Grapefruit	81	29–167
Lettuce	7400	680–8750
Onion	60	13–123
Peach	572	142–2089
Potato	25	15–40
Tomato	140	71–365

SOURCE S. Ben-Yehoshua (1987) ‘Transpiration, water stress, and gas exchange’, in J. Weichmann (ed.), *Postharvest physiology of vegetables*, Marcel Dekker, New York.

Produce characteristics

Surface area/volume ratio

Produce with a high surface area to unit volume ratio have a proportionally greater rate of transpiration. Individual edible leaves have surface area to volume ratios of around 50–100 $cm^2.cm^{-3}$, whereas tubers have ratios of about 0.5–1.5 $cm^2.cm^{-3}$. Therefore, with other factors being equal, a leafy vegetable will lose water much faster than a fruit. Similarly, a small fruit, root or tuber will lose water faster than a larger piece.

Plant surfaces

The structure and composition of plant surfaces and underlying tissues have a marked effect on the rate of water loss. Many produce such as tomatoes have a waxy cuticle on the surface. The cuticle is typically resistant to the passage of water or water vapour and plays an essential role in restricting water loss by evaporation and maintaining high water content within the tissue. It has been estimated that the cuticle reduces the rate of evaporation from living plant cells by around 25-fold.

The structure of the wax coating may be more important than its absolute thickness. Waxy coatings that consist of well-ordered overlapping platelets provide greater resistance to the permeation of water vapour than coatings that are without a tertiary structure. In the former case, water vapour must follow a more complex path as it escapes to the atmosphere.

The bulk movement of water vapour and other gases (oxygen, carbon dioxide) into and out of leaves is controlled by small pores called stomata. Stomata in harvested leafy produce are normally closed but under some conditions may remain open, such as during rapid cooling of chilling-sensitive tissues.

Many fruit (e.g. apple and avocado) and storage organs (e.g. sweet potato) have lenticels, and not stomata, on their surface. Lenticels are sunken openings that generally contain tightly packed and suberised hypodermal cells. Suberin, like cutin in the cuticle, is a hydrophobic compound that serves to minimise water loss. Otherwise, there is no mechanism for closing lenticels. Lenticels are often blocked, particularly in mature fruit, with wax and debris. In this case, loss of vapour water, and also respiratory gas exchange, may only take place by diffusion through the cuticle. In some harvested fruit (e.g. tomato), a large stem scar can also be an important route of water loss.

The surface of some roots and tubers (e.g. potato tubers) has a periderm made up of several layers of suberised (cork) cells which limit water loss when exposed to relatively low above-ground humidity after harvest. Curing is a postharvest process of short-term storage under high humidity and elevated temperature that encourages periderm formation (see Chapter 11).

Mechanical injury

Mechanical damage can accelerate the rate of water loss from harvested produce. Bruising, abrasion and removal of the natural wax covering from the surface structure increase water loss from the surface. Cuts both break the protective surface layer and directly expose underlying tissues to the atmosphere. Damage to surface tissue can also occur as a consequence of attack by pests (e.g. insects, rodents) or diseases and will result in increased rates of water loss. If damage occurs early in the growth and development of fresh produce, the organ may seal the affected area with a layer of corky callus cells. However, the capacity for wound healing generally diminishes as plant organs mature. Therefore, damage that occurs during harvesting and handling generally remains unprotected. Nonetheless, some types of mature produce (e.g. tubers and roots) retain the ability to seal wounds. If solutes such as sugars are released upon wounding, they may osmotically attract water vapour. A droplet will then grow in volume under conditions of high in-package humidity and continued release of solutes from the wound will accelerate microbial growth.

Management of water loss

There are two approaches to minimise water loss from horticultural produce: (1) management of the storage environment, and (2) minimising water loss capability of the produce by modifying the produce.

Natural cracks in the wax/cuticle in harvested produce are a route of water loss. Harvesting and handling of produce can also damage and remove surface waxes. Therefore, careful handling is a key measure to reduce water loss.

The most significant method of reducing water loss entails lowering the capacity of surrounding air to hold additional water. This can be achieved by lowering the temperature and/or raising humidity, thereby bringing about a reduction in the VPD between the product and air (Figure 5.2).

Reducing water loss by modifying the produce can be achieved with the use of edible coatings such as waxes and films. The commercial use of waxes on apples and oranges in many parts of the world replaces the natural waxes on the fruit, which are removed during postharvest washing and handling. There is considerable research and commercial interest in environmentally friendly edible coatings and films, which will reduce water loss and positively alter the internal atmosphere within the produce to maintain quality during storage. In many countries, food grade waxes such as carnauba and shellac-based waxes are already applied to increase the shine and gloss of the fruit, making it more attractive to consumers (Chapter 11).

Relative humidity

Increasing the RH of the air within the cool room reduces the VPD and therefore the amount of water lost from produce before the surrounding air is saturated. However, very high RH (>95%) can encourage the growth of bacteria or fungi, which may outweigh the potential benefits of reduced water loss on certain produce. In culture, most fungi cease to grow when the RH is reduced to about 90% and only a few can grow at 85%. Under drier conditions, spores cannot germinate and even if there is enough free moisture in a wound to permit germination, a dry atmosphere may dehydrate exposed tissue fast enough to prevent infection and development of a rot.

Recommended humidity conditions then become a compromise between reducing water loss and preventing microbial growth. For most produce, RH recommendations tend to be in the range of 85–95% RH, but can be 98% RH for produce with very high transpiration rates (e.g. leafy vegetables) and around 60% RH for produce highly susceptible to rotting (e.g. onions). A saturated atmosphere can only be utilised where produce have some resistance to rotting and/or are prone to excessive rates of water loss due to high coefficients of transpiration such as in leafy vegetables.

Storage of potatoes continuously at high humidity has an added advantage in that they are less prone to develop pressure bruises than if stored at low humidity. However, commodities such as potatoes and onions are more likely to sprout at high RH. In contrast to most harvested horticultural produce, onions and mature cucurbits (e.g. pumpkins) require a low in-storage RH of 60–70% to prevent excessive rotting.

It is relatively simple to increase the RH of air. Spraying water as a fine mist, and increasing the temperature of the refrigeration coils are practical methods. Addition of water vapour to a cold storage chamber can be controlled automatically with a humidistat. However, adding free water to a refrigerated system may result in condensation on the cold surfaces of produce, walls and cartons and also water pooling on floors. Moreover, increased frosting-up of refrigeration coils will necessitate longer and more frequent defrost cycles. For produce in cold rooms, the best way to maintain high RH (95%) is to maintain a small temperature difference between the refrigeration coils and the produce. This is done by using large coils with a high surface area for heat exchange (Chapter 7).

In the context of controlled ripening, fruit have a better appearance (less shrivelling) and internal quality if kept at >90% RH. The necessity to control RH in banana ripening rooms to prevent splitting and shrivelling is well recognised (Chapter 11). In contrast, storage of some apple cultivars at very high humidity can be a disadvantage – some weight loss from cultivars susceptible to internal or low temperature breakdown will decrease the incidence of the disorder.

Air movement

Air movement over produce significantly influences the rate of moisture loss. Therefore, while air movement is required to remove heat from produce, its effect on moisture loss must be considered. There is always a thin layer of unstirred air (the boundary layer) at the surface of produce. In this layer, the water VP is approximately in equilibrium with that of the produce itself. Increasing the rate of air movement reduces the boundary layer thickness, increasing the VPD near the surface and, thus, the rate of moisture loss. Restricting air movement around produce in a cool store can effectively reduce water loss.

Rapid air movement is required initially for fast cooling of warm produce. However, reduced air movement can subsequently be achieved by running fans on the evaporator at a lower speed or by reducing the length of time that they operate (Chapter 7). If storage is in open rooms with natural ventilation, modifications can be adopted to restrict air flow. Regulation of air movement requires compromise. Sufficient air movement is needed to prevent significant temperature gradients forming in the storage chamber but should be at rates that minimise water loss from produce. Maintaining a high RH by eliminating both VPD and air movement in a cool store system can be achieved by circulating cold air around smaller sealed plastic pallet shrouds or using carton liners.

Air pressure

Reduced air pressure, such as during vacuum cooling and during air freight under partial pressurisation conditions, will increase the rate of water loss from produce. The time that produce spends under reduced pressure conditions should be minimised and measures such as misting with water or provision of moisture barrier packaging should be taken to inhibit water loss. Indeed, some modern vacuum sea containers have automated humidity adjustment to maintain high RH.

Packaging

Water loss can be effectively reduced by placing a barrier around produce which prevents surface air movement. Simple methods are to pack produce into bags or boxes and to cover stacks of produce with tarpaulins. Close packing of produce itself restricts the passage of air around individual items and, thereby, reduces water loss. Thus, even placing produce in mesh bags can be beneficial because the closer packing will lead to thicker unstirred boundary layers around inner produce items.

The degree to which water loss is reduced by packaging depends on the permeability of the package to water vapour transfer as well as on the closeness of containment. Most common packaging materials are permeable to water vapour to some extent. However, plastic (e.g. polyethylene) films are excellent vapour barriers. Their rate of water vapour transfer is extremely low compared to that of paper, but even paper bags and fibreboard packages will substantially reduce water loss compared with loose produce. Conversely, packaging also reduces the rate of cooling by restricting air movement around individual items.

The use of very thin plastic wrap and heat-shrink films for packaging individual fruit can significantly increase the storage life of many produce by greatly reducing water loss. Such films are used in the marketing of some types of cucumbers and offer storage in a water vapour saturated atmosphere without the problem of condensation. Theoretically, condensation cannot occur because the film is very thin (ca. 10–50 μm) and the produce and the film are in intimate contact and hence at exactly the same temperature. However, there are often areas where the produce and the film are not in contact (e.g. stem scars). Condensation can occur in these locations and can promote fungal development.

It is important to consider the ability of many packaging materials to absorb moisture vapour and water. Paper derivatives, jute bags and other natural fibres can absorb considerable amounts of moisture before becoming visibly damp. At the time of packing, there is often a significant VPD between the produce and the package. Thus, water evaporated from the produce may be absorbed by the packaging material. In the cool storage of apple and pear fruit, it has been found that a dry wooden box weighing 4 kg will absorb about 500 g of water at 0°C. Ideally, packages should be equilibrated at high humidity before use, but this is impractical commercially. An alternative procedure is to waterproof moisture absorbent packaging materials like fibreboard with wax or resin coatings, or to use a non-absorbent packaging material such as plastic (e.g. PET).

The ability of certain packaging and other materials to absorb and desorb moisture can be exploited to achieve moisture management within packages. For instance, a dry paper liner can be inserted into a modified atmosphere package to help control in-package RH. Such moisture sinks are used to lower RH when wet cherries are freshly packed and to avoid free water accumulation and condensation in a package. In turn, the risk of disorders such as a fruit splitting or decay is reduced. Conversely, moisture sinks with sufficient sorption capacity can work as reservoirs or moisture stores, which can supply water vapour to dehydrating produce in a package.

It is important that these principles and considerations not only apply to on-farm and packinghouse cool rooms but also through the supply chain, including the retail environment. A critical point in the supply chain where postharvest principles are often compromised is at the market and retail shelf. This time should be kept to a minimum as some postharvest deterioration does occur. It is important to maintain good postharvest practices for as long as possible to maintain produce quality for the consumer.

6
Storage atmosphere

The composition of gases in the storage atmosphere can affect the storage life of fruit and vegetables. Atmospheric air contains about 78% nitrogen, 21% oxygen and 0.04% (400 μL/L) carbon dioxide, and altering the concentrations of the respiratory gases, oxygen and carbon dioxide can be used to extend the storage life of produce. This is generally used as an adjunct to low temperature storage, but for some commodities modification of the storage atmosphere can usefully substitute for refrigeration. In addition, many volatile compounds evolved by produce and from other sources may accumulate in the storage atmosphere. Ethylene is the most important of these compounds and its accumulation above certain critical levels can reduce storage life, so methods for its control can become important.

There is a range of terminology associated with changing the storage atmosphere. Controlled atmosphere (CA) storage generally refers to decreased oxygen and increased carbon dioxide concentrations and there is control of the level of these gases. Modified atmosphere (MA) storage is when the composition of the storage atmosphere is not closely controlled, although it is often used as a generic descriptor of any storage that involves change in the atmosphere. Modified atmosphere packaging (MAP) refers to packages and film box liners that are used to alter the composition of the atmosphere around produce.

The concentration of gases in the atmosphere should correctly be stated in SI units as partial pressures (i.e. kPa), but most postharvest workers prefer to use per cent v/v. However, at atmospheric pressure, partial pressures in kPa are numerically close to per cent; for example, 1% = 1.013 kPa and 20% = 20.26 kPa.

Carbon dioxide and oxygen

The general equation for produce respiration:

glucose + oxygen → carbon dioxide + water

suggests that respiration could be slowed by limiting the oxygen or by raising the carbon dioxide concentration in the storage atmosphere. This principle appears to have been applied in ancient times, even if unwittingly. Some of the earliest use of modified atmosphere storage may be attributed to the Chinese, as ancient writings report that litchis were transported from southern China to northern China in sealed clay pots to which fresh leaves and grass were added. It may be surmised that during the two-week journey, respiration of the fruit, leaves and grass generated a high carbon dioxide/low oxygen atmosphere in the pots, which retarded the ripening of the litchis. The first reported scientific observations of the effects of atmospheres on fruit ripening were made in 1819–20 by Jacques Berard in France, but it was not until the work of Kidd and West at the Low Temperature Research Station in Cambridge, UK in the 1920s and 1930s that a sound basis for the modified atmosphere storage of fruit and vegetables was established.

The effects of modified atmospheres have since been extensively tested on a wide range of fruit and vegetables, but the responses vary considerably. Despite this extensive research, major commercial application of controlled atmospheres has been mainly been with some apple and pear cultivars, although modified atmospheres have been more successfully applied during transport to a range of produce such as cherries. It is of considerable relevance for minimally processed produce, especially sliced lettuces, due to their short shelf life and susceptibility to browning (see Chapter 12).

Factors which have influenced the adoption of modified atmospheres for different commodities include:

- Inherent storage life in air. If the produce can be stored in a satisfactory condition in air for the desired marketing period, there is no need to use atmosphere modification to prolong storage life.
- Existence of a distinct beneficial effect. Not all produce respond favourably to atmosphere regulation and some are little affected.
- Substantial atmosphere tolerance. The beneficial effects of atmosphere modification, especially in MA storage, need to be sustained over a relatively wide concentration range. A small tolerance range will result in variable quality outturns due to insufficient or excessive gas concentrations.
- Seasonal availability. Use of modified atmospheres can be advantageous where produce is harvested over a relatively short period in the year. Extending the storage life of such produce can give greater marketing flexibility.
- Availability of substitute commodities. While produce may be stored satisfactorily in modified atmospheres, it

may be more economical to import produce from another region or country that has a different harvest period.
- Availability of alternative cost-effective technology to maintain quality, such as 1-methylcyclopropene (see later in this chapter).
- An economic benefit is derived. There needs to be a clear financial gain from the use of atmosphere control.

Metabolic effects

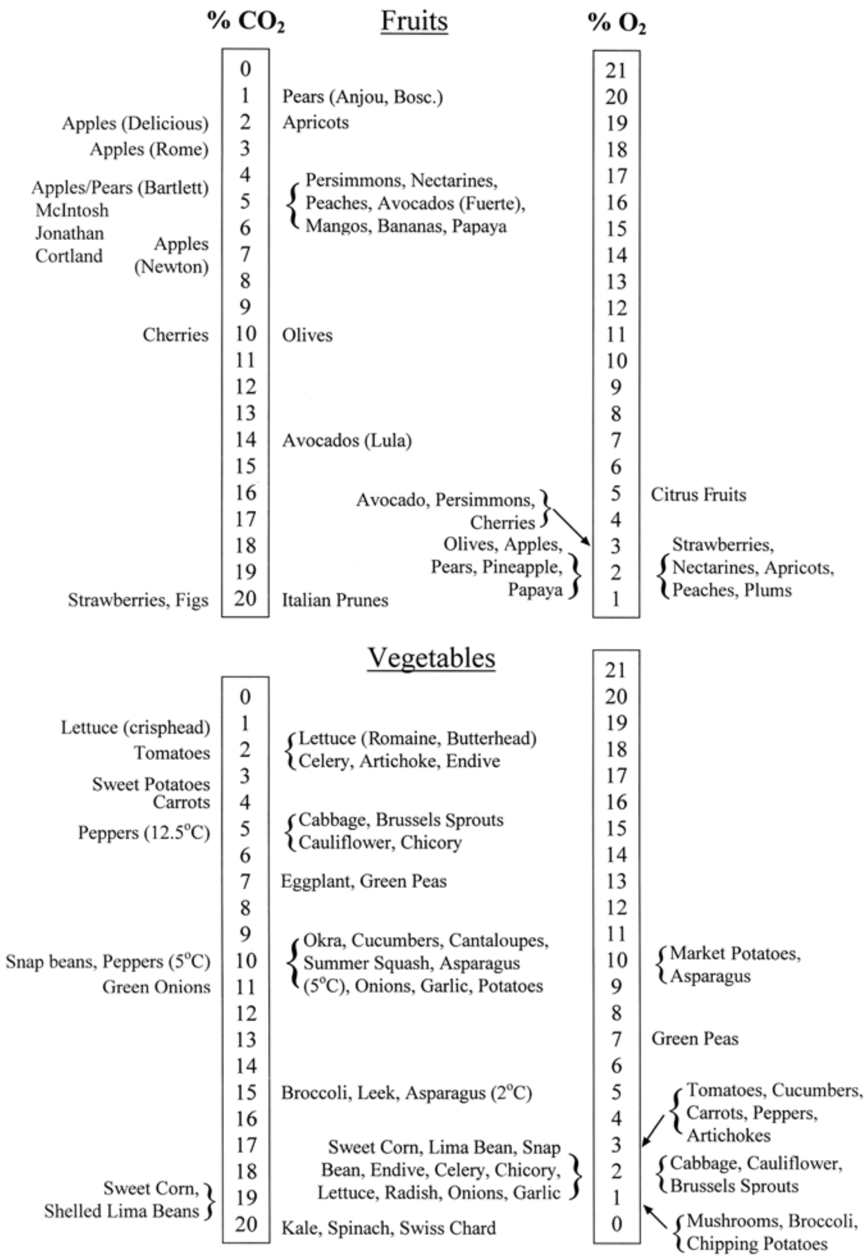
Increases in carbon dioxide and decreases in oxygen concentrations exert largely independent effects on respiration and other metabolic reactions. Generally, the oxygen concentration must be reduced to less than 10% (by volume) before any retardation of respiration is achieved. For apples stored at 5°C, the oxygen level must be reduced to about 2.5% to achieve a 50% reduction in respiration rate. Care must also be taken to ensure that sufficient oxygen is retained in the atmosphere so that anaerobic respiration, with its associated development of off-flavours, is not initiated.

The reduction in the concentration of oxygen necessary to achieve a retardation of respiration is dependent on the storage temperature. As the temperature is lowered, the threshold concentration of oxygen for a beneficial effect is also reduced. The critical level of oxygen at which anaerobic respiration occurs is determined mainly by the rate of respiration and is therefore greater at higher temperatures. Tolerance to low oxygen levels varies considerably among different commodities and even among cultivars of the same commodity. The critical level of oxygen may vary with the time of exposure, with lower levels being tolerated for shorter periods. It may also be affected by the level of carbon dioxide, since lower levels of oxygen often seem to be better tolerated when carbon dioxide is absent or at a low level.

The addition of only a few per cent of carbon dioxide to the storage atmosphere can have a marked effect on respiration. However, if carbon dioxide levels are too high, effects similar to those caused by anaerobiosis (lack of oxygen) can be initiated. Responses to increased carbon dioxide levels vary even more widely than responses to reduced oxygen. For example, strawberries will benefit from exposure to 30% carbon dioxide for short periods, while some apple cultivars are injured by 2% carbon dioxide in storage and many vegetables appear to respond best to low oxygen when carbon dioxide is kept low or is absent. Figure 6.1 shows the tolerance of various produce to low oxygen and high carbon dioxide.

Many of the beneficial results of modified atmosphere storage cannot simply be attributed to a reduction in respiration. For example, under ideal experimental conditions a 12-fold increase in the storage life of green bananas can be achieved by ventilating the fruit with an atmosphere comprising 5% carbon dioxide, 3% oxygen and 92% nitrogen in the absence of ethylene, but respiration measured in terms of oxygen uptake is reduced to only one-quarter of the rate in air. The greatly increased storage life is attributed to a reduction in the rate of natural ethylene production by the bananas and a reduced sensitivity of the fruit to ethylene.

Due to its sensory importance, the effect of modified atmospheres on aroma production is of enormous commercial interest. For climacteric fruits, the characteristic aroma production in many fruits starts after the climacteric rise of ethylene



% CO_2
Fruits
% O_2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
Pears (Anjou, Bosc.)
Apples (Delicious)
Apricots
Apples (Rome)
Apples/Pears (Bartlett)
McIntosh
Jonathan
Cortland
Apples (Newton)
Persimmons, Nectarines, Peaches, Avocados (Fuerte), Mangos, Bananas, Papaya
Cherries
Olives
Avocados (Lula)
Avocado, Persimmons, Cherries
Citrus Fruits
Olives, Apples, Pears, Pineapple, Papaya
Strawberries, Nectarines, Apricots, Peaches, Plums
Strawberries, Figs
Italian Prunes
Vegetables
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
Lettuce (crisphead)
Tomatoes
Lettuce (Romaine, Butterhead) Celery, Artichoke, Endive
Sweet Potatoes
Carrots
Peppers (12.5°C)
Cabbage, Brussels Sprouts Cauliflower, Chicory
Eggplant, Green Peas
Snap beans, Peppers (5°C)
Green Onions
Okra, Cucumbers, Cantaloupes, Summer Squash, Asparagus (5°C), Onions, Garlic, Potatoes
Market Potatoes, Asparagus
Green Peas
Broccoli, Leek, Asparagus (2°C)
Tomatoes, Cucumbers, Carrots, Peppers, Artichokes
Sweet Corn, Lima Bean, Snap Bean, Endive, Celery, Chicory, Lettuce, Radish, Onions, Garlic
Cabbage, Cauliflower, Brussels Sprouts
Sweet Corn, Shelled Lima Beans
Kale, Spinach, Swiss Chard
Mushrooms, Broccoli, Chipping Potatoes

Figure 6.1 (left) **Relative tolerance of fruit and vegetables to elevated carbon dioxide and reduced oxygen concentrations at recommended storage temperatures. Normal atmospheric air comprises 0.04% carbon dioxide, 21% oxygen and about 79% nitrogen.**

SOURCE A.A. Kader and L.L. Morris (1977) 'Relative tolerance of fruits and vegetables to elevated CO_2 and reduced O_2 levels', in D.H. Dewey (ed.), *Controlled atmospheres for storage and transport of horticultural crops*, Michigan State University, East Lansing MI: 260–65.

production. CA storage in particular has been shown to suppress aroma production in apples, although with time volatile production rates return to acceptable limits.

In green vegetables, improved retention of green colour in low oxygen atmospheres is due mainly to a lowering of the rate of chlorophyll destruction. A contrasting effect has been noted in potatoes, where greening due to exposure to light can be prevented for several days by maintaining tubers in an atmosphere containing about 15% carbon dioxide.

Modified atmospheres, particularly those containing high carbon dioxide, inhibit breakdown of pectic substances so that a firmer texture is retained for a longer period. However, increased carbon dioxide aids in retention of organic acids in tomatoes but accelerates loss of acids in asparagus. In addition, a range of physiological disorders can develop (see Chapter 8). Because of the widely varying responses of different commodities to alterations in oxygen and carbon dioxide concentrations, ideal combinations need to be determined experimentally for each commodity and cultivar.

Effect on decay and insect pests

The activity of several decay organisms can be reduced by atmospheres containing 10% carbon dioxide, provided the commodity itself is not injured by such high carbon dioxide levels. Since strawberries can tolerate high carbon dioxide, transport of strawberries under modified atmosphere has been found to significantly reduce rotting and give a valuable extension in marketing life and quality. Produce that cannot tolerate high carbon dioxide levels may require a lower carbon dioxide level to give some reduction in rotting by retarding ripening and senescence – the natural resistance of produce to pathogens decreases as it ripens or ages. In contrast, some fruits, such as bananas and mangoes, respond well to atmosphere control but eventually lose their resistance to the latent anthracnose disease, which then becomes the factor limiting storage life.

CA storage has been used as a quarantine treatment in combination with heat or cold to reduce duration of the lethal treatment and to help to maintain commodity quality (see Chapter 11). For example, the controlled atmosphere temperature treatment system (CATTS) is a quarantine treatment that utilises forced air vapour heat under conditions of controlled levels of low oxygen and high carbon dioxide. Incorporation of the CA allows reduction in treatment time, which minimises commodity damage due to the heat while still maintaining the required treatment efficacy.

Controlled atmosphere storage

The earliest commercial applications of controlled atmosphere storage relied on the produce to generate the storage atmosphere, which was generally in the range of 5–10% carbon dioxide and 16–11% oxygen. Low oxygen levels were then found to be of greater benefit but a higher level of carbon dioxide was not required. This resulted in the development of systems where the storage chamber was made more gas-tight and an external generator that burnt fuels such as petroleum gas was attached to rapidly reduce the initial level of oxygen in the chamber. Excess carbon dioxide produced from the generator and ongoing produce respiration was removed by recirculation of the storage atmosphere through a scrubber. The controlled admission of some air into the storage room prevented the oxygen level becoming too low during storage.

Current technologies used to generate CA include hollow fibre systems and pressure swing adsorption systems (described in Chapter 7) that provide a consistent supply of low oxygen for continuous ventilation of produce. An advantage of these techniques is that the starting raw material, regular air, is freely available and no hazardous gaseous by-products are generated. However, the atmosphere needs to be constantly monitored and remedial action taken to prevent undesirable low and high levels of oxygen and carbon dioxide, respectively. These developments allow an effective atmosphere, especially for many apple cultivars, containing 2–5% carbon dioxide and 2–3% oxygen to be quickly established and maintained for long periods.

However, with more efficient methods to generate, monitor and maintain tight control on atmospheres, improvements in fruit quality and reduction in some storage disorders can be made with even lower oxygen levels. For example, a major storage physiological disorder in apples, superficial scald, has been shown to be reduced with ultra low oxygen (around 1%)

levels. In addition, protocols such as an initial low oxygen stress followed by normal CA storage have been shown to control superficial scald – oxygen is set at 0.5% for two to three weeks at the start of storage and then raised to 1.5%, with the temperature raised to 2°C for three to four days. The temperature is then lowered to 1°C and oxygen increased to 1.5% for the remainder of an eight-month storage period.

A problem with set or fixed CA systems is that the maximum benefit from the CA investment is at the lowest levels of oxygen but this carries the greatest risk of the produce undergoing anaerobic metabolism. Setting ultra-low oxygen levels near the anaerobic threshold runs the risk that the fruit will shift from aerobic to anaerobic respiration. This causes accumulation of acetaldehyde and ethanol and other off-flavours.

More recent developments have been in dynamic CA systems (DCA) where the CA conditions are dynamically altered during the storage period. The technology used for the DCA responds to the physiological condition of the fruit and automatically adjusts the storage conditions accordingly, based on the produce response to the low oxygen. Oxygen at less than 1% is thus not a problem, as the oxygen concentration will be immediately amended if the produce responds adversely. Technologies supporting DCA systems in monitoring produce stresses include real-time measurement of ethanol production, fruit respiration, and chlorophyll fluorescence in the CA store. For example, continuous non-destructive measures of chlorophyll fluorescence of the apple peel can detect when chloroplasts are stressed – a characteristic chlorophyll fluorescence signal is detected and the DCA system vents more air into the cool store. This increases the levels of oxygen in the CA room, alleviating the potential for anaerobic respiration and stress. The vent is then shut to maintain the low level of oxygen within the CA store.

CA is not limited to large static cool stores. A range of CA technology is available in shipping containers for the long distance transport of perishable produce. Chapter 7 describes the different commercial CA shipping containers which can either actively or passively regulate the concentration of oxygen and carbon dioxide inside the refrigerated container during transport.

Modified atmosphere storage

The use of modified atmospheres within portable packages has considerable commercial appeal and they are widely used in some industries, such as cherries. Polyethylene film bags are a relatively cheap and widely available packaging material used as a horticultural box liner, with the bag being sealed or remaining unsealed. Unsealed or perforated bags are commonly used to minimise weight loss and reduce abrasion damage, while sealing the bag will also generate a modified atmosphere.

However, it is important to maintain the cool chain and prevent any breaks or increases in storage temperatures when using sealed bags, because the permeability of the film to gases is virtually independent of temperature over the normal postharvest range, whereas respiration is strongly temperature-dependent. A break in the cool chain, with an increase in produce temperature leading to an increase in the respiration rate, will alter the desired modified atmosphere within the package and will often result in variable produce quality at the market. Thus, the use of sealed bags is risky when the temperature varies more than a few degrees, unless the produce has a low rate of respiration, or is tolerant to atmospheres which vary widely in carbon dioxide and oxygen concentration or both.

The commercial availability in recent years of a range of new food-grade polymeric films with differing permeability to the atmospheric gases has revived interest in packaging produce in sealed bags. In addition, the availability of MA pallet bags/shrouds which seal over an entire pallet of produce packed in cartons allows a modified atmosphere to be generated on the pallet scale rather than within an individual carton. The use of such films and techniques for refrigerated produce offers a cheaper alternative to using large containers equipped to provide modified or controlled atmosphere conditions. In addition, newer films remove many of the risks of modified atmosphere storage and are often marketed as 'smart' or 'active' packaging. The types of film used in MA are discussed in Chapter 11.

Hypobaric storage

Hypobaric storage is a form of CA storage in which produce is stored in a partial vacuum. A reduction in the pressure of air to 10 kPa (0.1 atmosphere) is equivalent to reducing the oxygen concentration to about 2% at normal atmospheric pressure. The vacuum chamber is vented continuously with water-saturated air to maintain oxygen levels and to minimise water loss. Ripening of fruit is retarded by hypobaric storage due to the reduction in the partial pressure of oxygen and for some fruits also to the reduction in ethylene levels. Hypobaric stores are expensive to construct because of the low internal pressures utilised, and this high cost of application appears to be limiting the use of hypobaric storage to high-value produce. However, the engineering and construction costs of hypobaric chambers have reduced over time and commercial hypobaric shipping containers are available for the transport of high-value perishable produce.

Ethylene

The commencement of natural ripening in climacteric fruits is accompanied by an increase in ethylene production, but treatment of preclimacteric fruits with exogenous ethylene will advance the onset of ripening. This response is used widely in commercial practice to achieve controlled ripening of fruits such as bananas which are picked and transported in a mature but unripe state and ripened just before marketing (Chapter 11). However, the action of ethylene must be avoided for such fruit during storage and transport to prevent premature ripening. In contrast, the effect of ethylene on non-climacteric fruit and vegetables generally offers little commercial benefit but will reduce postharvest quality by promoting senescence as evidenced by loss of green colour, change in texture and flavour, and by enhancement of low temperature injuries and microbial decay. In some instances, the effect of ethylene on non-climacteric fruit can be beneficially utilised, such for as the controlled degreening of citrus fruit (see Chapter 11).

While the levels of ethylene that trigger ripening have been well researched for most climacteric fruits, the threshold concentration that enhances senescence in non-climacteric fruit and vegetables is less well documented. A concentration of 0.1 microlitre per litre of ethylene is often cited as the threshold level, but some studies indicate that the threshold level of ethylene is less than 0.005 microlitre per litre. For practical purposes, this means there is no safe level of ethylene and hence any reduction in ethylene concentration will bring some extension in postharvest life at higher storage temperatures.

Ethylene in a storage or transport container may come from the produce itself or from outside sources. Often during marketing, several commodity types are stored together, and ethylene given off by one commodity can adversely affect another. In addition, exhaust gases from internal combustion engines (including forklifts) and leakage of natural gas that contains ethylene from cylinders or reticulated pipes will contaminate stored produce sufficiently to initiate ripening in fruit and promote senescence in non-climacteric produce. The level of deleterious action will depend on the concentration of ethylene that accumulates and the duration of exposure. The wide range in concentration of ethylene that might be found in various situations is summarised in Table 6.1.

Table 6.1 Ethylene levels in ambient and postharvest situations

Area	Ethylene concentration (µL/L)
In air – rural	<0.001 to 5
– urban areas	<0.05
– heavy traffic	Up to 1
Industrial areas	Up to 0.16
Supermarkets	0.017–0.035
Wholesale markets	0.06
Domestic refrigerators	0.03–0.2
Apple and pear cool stores	Up to 30
Inside packages	Up to 48

SOURCE Adapted from N. Keller, M.N. Ducamp, D. Robert and V. Keller (2013) ‘Ethylene removal and fresh product storage: A challenge at the frontiers of chemistry. Toward an approach by photocatalytic oxidation’, *Chemical Reviews* 113: 5029–70.

In addition to delaying ripening or senescence through reducing ethylene concentrations around produce, the sensitivity of produce to ethylene may be lessened by storage at low temperature and by raising the level of carbon dioxide or decreasing the level of oxygen. Under these conditions, the amount of ethylene required to induce ripening is increased. A similar effect has been demonstrated for some non-climacteric produce; for example, the ethylene-induced breakdown of chlorophyll in broccoli is less sensitive to ethylene at low temperatures.

Since reducing ethylene levels around produce has a similar effect to lowering the storage temperature, managing ethylene can in some situations reduce the need for refrigeration. This is relevant to the desire by industry and the community to reduce greenhouse gas emissions by reducing energy usage (discussed in Chapter 12). Improved management of ethylene can have particular relevance in less developed countries, where it is often not possible to maintain a postharvest cool chain.

Methods for reducing the effects of ethylene

There are two approaches to reduce the effects of ethylene on product quality: (1) remove ethylene from the atmosphere, and (2) inhibit ethylene synthesis/action.

Avoidance of ethylene accumulation

Reduction of ethylene levels in storage rooms can be achieved by good housekeeping; that is, storing ripe and unripe produce in separate rooms, regularly removing all rotted or damaged produce, and ensuring that natural gas pipes and cylinders and exhaust gases from internal combustion engines are kept well away from storage rooms.

A simple physical method to minimise ethylene accumulation is to ensure good ventilation of the storage chamber with air from outside the storage complex. The ethylene concentration in the atmosphere is normally less than 0.005 microlitre per litre unless there is contamination from nearby industrial sources or heavy automobile traffic (Table 6.1). Ventilation with external air could be applicable where no large temperature differential exists between the external air and the storage chamber, provided it is at an appropriate relative humidity. Enhanced water loss from produce can be an issue if the humidity of the external air is low. If there is a large temperature difference, it may be necessary to cool the air before admitting it to the chamber. The use of efficient heat exchangers has resurrected interest in ventilation for use in cool stores, and commercial ventilation units are now being marketed.

Oxidation with potassium permanganate

Ethylene in the atmosphere can be oxidised to carbon dioxide and water using a range of chemical agents. Potassium permanganate is effective in reducing ethylene levels and since it is non-volatile, it can be physically separate from produce, thus eliminating the risk of chemical injury to produce. To ensure efficient destruction of ethylene, a large surface area of potassium permanganate is achieved by coating an inert inorganic porous support such as alumina or expanded mica with a saturated solution of potassium permanganate. The ability of potassium permanganate to delay ripening has been demonstrated in a range of climacteric fruits such as bananas, avocados, mangoes and kiwifruit and non-climacteric produce such as lemons, lettuce and strawberries.

Table 6.2 demonstrates the benefit to be obtained with bananas when potassium permanganate is used in conjunction with modified atmosphere storage in polyethylene bags. The high carbon dioxide and low oxygen atmosphere generated within the sealed bags decreases the response by bananas to ethylene, while the addition of potassium permanganate further retards ripening by maintaining ethylene at a low level for a long period. The presence of a high humidity in storage containers is a limitation to the longevity of potassium permanganate absorbents, as it also reacts with water. While the extent of commercial use of potassium permanganate alone or in conjunction with modified atmosphere is difficult to document, the Australian navy has used tubes of potassium permanganate in fruit and vegetable chambers on board its vessels and a range of retail products designed for use in both commercial and domestic cool stores are widely marketed.

Table 6.2 Shelf life of bananas held at 20°C in modified atmospheres with potassium permanganate

Treatment	Shelf life (days)
Air	up to 7
Sealed polyethylene bags	14
Sealed bags + potassium permanganate	21

SOURCE Adapted from K.J. Scott, W.B. McGlasson and E.A. Roberts (1970) 'Potassium permanganate as an ethylene absorbent in polyethylene bags to delay ripening of bananas during storage', *Australian Journal of Experimental Agriculture and Animal Husbandry* 10: 237–40.

Oxidation with ozone

Ozone (O_3) is a suitable oxidising agent for destroying ethylene as it is generated readily from atmospheric oxygen by an electric discharge or ultraviolet radiation, and since it is gaseous, it readily mixes and reacts with ethylene. Another benefit of ozone is its strong antimicrobial properties. Ozone has been found to be effective against spores and fungi, but can also cause irreversible damage to produce. Some precautions must be taken with ozone: it is highly reactive and will corrode metal pipes and fittings in refrigeration equipment and react with paper products used to package produce. In addition, ozone can be toxic to humans at relatively low concentrations (discussed further in Chapter 7). The widespread use of ozone has been hampered by difficulties in controlling its concentration and potential deleterious human health effects.

Oxidation by photocatalysis

Photocatalysis is an emerging and promising technology and involves the use of semiconductor materials such as titanium dioxide which are excited by energy supplied by the direct absorption of light. The release of this energy is sufficient to oxidise ethylene to carbon dioxide and water. Many new photocatalytic devices claim high photocatalytic efficiency due to their high quantum yield, stability toward photo corrosion and chemicals, insolubility in water, low toxicity and low cost.

Adsorption onto solids

A wide range of microporous earth-derived materials and minerals have the ability to adsorb ethylene onto their surface and thereby remove it from the storage atmosphere. Such materials include zeolites (which are aluminosilicates), clays and carbon-based materials such as activated carbon. Their adsorption capacity depends on having a high surface area per unit weight. Over the years most of these materials have been shown to have a lower capacity to remove ethylene compared to ethylene scrubbers such as potassium permanganate. However, they have been utilised in packaging to reduce the accumulation of ethylene in sealed packages.

Inhibition of ethylene synthesis and action

Blocking the action of ethylene was achieved in the 1970s by dipping produce in a solution containing silver ions which bind strongly to the enzyme receptor site occupied by ethylene. While the cut flower industry uses this treatment, silver is a highly toxic heavy metal and cannot be used with fruit and vegetables. Even with ornamental usage, there is considerable environmental concern arising from the disposal of waste dip solutions and treated flowers.

The use of 1-methylcyclopropene (1-MCP) to inhibit the synthesis of ethylene is probably the greatest innovation and most researched topic in postharvest horticulture over the last 20 years. The technology emerged from the laboratory of Ed Sisler at North Carolina State University (USA) in the mid-1990s. These researchers showed that exposure to concentrations of 1-MCP at only nanolitres per litre for a few hours was sufficient to inhibit abscission in various ornamentals. Numerous studies since then have shown 1-MCP to generate a beneficial effect on a wide range of fruit and vegetables. The action of 1-MCP is considered to occur due to a physical similarity to ethylene that allows it to strongly bind to the metal in the ethylene receptor for a long period and therefore the produce will not respond to ethylene.

The effects of 1-MCP, such as a reduction in respiration and volatile synthesis and loss of chlorophyll, are typical of delayed ripening and senescence arising from preventing the action of ethylene. In addition, 1-MCP can also reduce the incidence of some physiological disorders of apples. 1-MCP is registered for commercial use in many countries, but commercialisation has tended to focus on extending the storage life of apples, particularly through a delay in softening and control of superficial scald. It is currently applied as a gas, but a liquid formulation and a sachet-type product are potential alternatives. 1-MCP is considered safe in terms of having no mammalian toxicity and no adverse environmental impacts.

The use of 1-MCP is not without potential problems, which stem from the irreversible nature of its binding to the ethylene receptor, which stops all ripening. However, at some stage during storage, fruits will need to be ripened for marketing. This will require the generation of new ethylene receptors by the fruits. This may result in variable ripening in respect to time to ripen and the quality of ripe fruits.

The commercial success of 1-MCP can be attributed in large part to the existence of patent protection. This has allowed the patent holder to provide considerable support to many international research groups to demonstrate the effects of 1-MCP and to then overcome the complex regulatory environment to obtain registration in many countries. In the current environment, the lack of patent protection is a significant impediment to commercialisation of any new chemical based-technology.

Treatment with ethylene synthesis inhibitors is also an alternative, or perhaps adjunct, to treatment with ethylene binding site blockers. For example, the preharvest application of aminoethoxyvinylglycine (AVG, Retain™) to apple fruit in the orchard allows them to reach greater maturity and colour prior to harvest. From a postharvest perspective, a potential drawback of ethylene synthesis inhibitors is that they only confer protection against endogenously (internally) produced, and not exogenous (external), ethylene.

Another approach to reducing or eliminating ethylene effects is by genetic engineering. The molecular biology of ethylene synthesis is becoming well known, and there have been a range of genetically engineered fruit with suppressed ethylene responses. However, the current regulatory and consumer resistance to genetically engineered produce is likely to limit commercial application.

Other gases in the storage environment

In addition to carbon dioxide, oxygen and ethylene, a range of other gases have been studied and have some use in the storage of fruit and vegetables.

Two oxides of nitrogen, nitrous oxide (N_2O) and nitric oxide (NO), have been reported to extend the postharvest life of a range of horticultural produce, albeit by vastly differing methodologies. Nitrous oxide is a stable gas that is used at quite high concentrations (20–80%) as a replacement for nitrogen in the storage atmosphere. Nitrous oxide is presumed to suppress metabolism similar to carbon dioxide as both compounds have a similar structure, but nitrous oxide is tolerated by produce at much higher concentrations. However the postharvest benefit of nitrous oxide is only achieved while the nitrous oxide is present.

Nitric oxide is a highly reactive free radical gas and is applied as a short-term treatment (hours) at relatively low concentrations (μL/L), with a long-term benefit for a wide range of produce. The mode of action is not yet understood but is expected to be multi-faceted, in parallel with the many effects nitric oxide has been found to have on mammalian physiology. Nitric oxide has a potential advantage in that it is a natural metabolite of both mammals and plants, but its metabolism in plants is not identical to mammalian synthesis. Without patent protection, it is questionable who will undertake the necessary investigations to gain regulatory approval. An alternative strategy is to find generally regarded as safe (GRAS) compounds or other benign agents such as yeast extracts that can stimulate the endogenous production of nitric oxide.

Carbon monoxide (CO) is not evolved by fresh produce, but with some produce it shows effects which mimic those induced by ethylene and there are examples of beneficial responses to added carbon monoxide (e.g. the control of butt discolouration and retardation of the growth of *Botrytis* rots in lettuce). However, carbon monoxide is toxic to humans at relatively low levels and any commercial usage would require a stringent safety regime to be in place.

There has been growing interest in a range of other gases in the storage environment to control postharvest diseases and physiological disorders. For example, a role in quality maintenance for other organic volatiles such as acetaldehyde and ethanol evolved by produce has been studied, particularly in relation to the antimicrobial properties of certain compounds. Ethanol vapour has also been shown to markedly reduce the incidence of superficial scald in apples. In addition, the use of essential oils and GRAS compounds are being actively studied for their control of postharvest decay.

7
Technology of cool storage

Reducing produce temperature is the most effective method of minimising the loss of quality of fruit and vegetables during storage (Chapter 4). The fundamental rule for optimum maintenance of quality is to store produce at the lowest possible temperature and to minimise the loss of water. The lowest safe temperature is just above the freezing point except for produce susceptible to low temperature physiological disorders (Chapter 8), where the threshold for development of the disorder becomes the lower limit. Application of these principles has led to the development of equipment and systems for controlling temperature and humidity of the air around produce.

However, refrigerated storage is expensive to install and large amounts of energy are consumed to maintain the desired low temperatures. It is therefore important to ensure that returns from the stored produce justify the expenditure. This may mean storing at temperatures higher than the optimal in a more economical structure or operating system.

Temperature management

In-ground storage

Pit storage, or clamp storage, is a simple low-technology on-farm technique that is still beneficially practised in some countries. Hard vegetables, such as potatoes, turnips and late-season cabbages, are piled into pits dug into a hillside or in some other well-drained position. The pits are lined with hay or straw and the produce is covered with straw followed by 10–20 cm of earth to protect against freezing or excess heat and

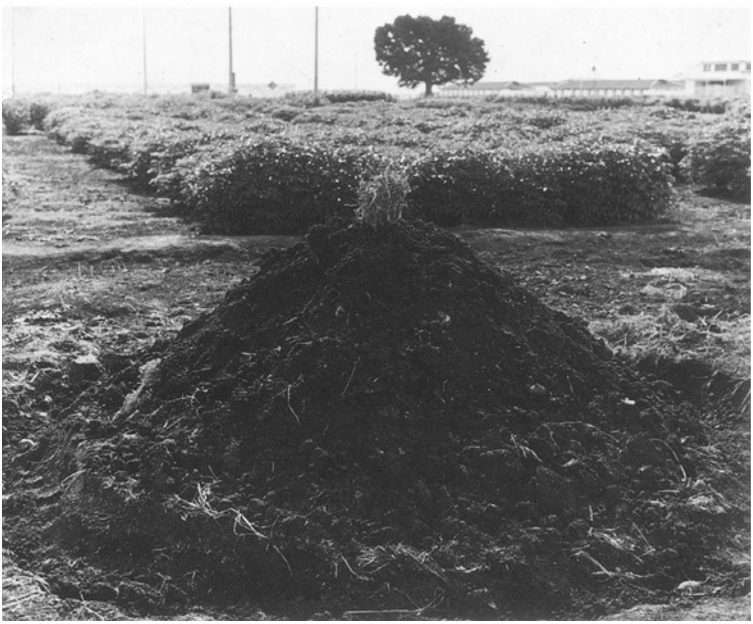


Figure 7.1 Cassava storage clamp

SOURCE Courtesy of R.H. Booth, Food and Agriculture Organization of the United Nations, Rome.

to deflect rain. The inclusion of piped ventilation to the outside to reduce respiratory self-heating is an advantage. Clamp storage has been shown to be suitable for storage of cassava for up to two months in the tropics (Figure 7.1).

In Europe and North Asia, perishable produce was historically stored in cellars and caves that were cooler than above-ground buildings in summer and warmer in winter. These methods are still practised in some parts of the world. The performance of cellars is improved by providing controlled ventilation openings for the entrance of cold air and exit of warm air by convectional circulation when cooling is required.

Air-cooled stores

Air-cooled stores are simple insulated structures above ground, or partly underground, which are cooled by the circulation of colder, outside air. When the temperature of the produce is above the desired level and if the temperature of the outside air is lower (generally at night), air is circulated throughout the store by convectional or mechanical means through bottom inlet vents and top outlets fitted with dampers. Fans may be installed and controlled manually or automatically with differential thermostats. The air may be humidified, a process that can also be automated. Air-cooled stores are relatively cheap to construct and operate and are still widely used for the storage of potatoes and sweet potatoes, both of which need relatively high storage temperatures to avoid accumulation of sugar and chilling injury, respectively.

Ice refrigeration

An advance on air-cooled storage was the use of natural ice as a refrigerant. The melting of 1 kilogram of ice absorbs 325 kilojoules of heat energy, but the considerable bulk of ice needed and the disposal of the melt water are disadvantages. Ice produced by mechanical refrigeration has several modern commercial applications as an adjunct to refrigeration (Chapter 4). For example, ice is used to supplement the cool chain in the transport and storage of broccoli. But potential issues with non–food-grade water/ice may restrict this use.

Mechanical refrigeration

A refrigeration plant consists of four basic components: (1) the compressor in which the refrigerant gas is compressed (and unavoidably heated); (2) the condenser, either air-cooled or water-cooled, in which the hot gas is cooled and condensed to a liquid; (3) the expansion valve; and (4) the evaporator coils in which the liquid is permitted to boil and so remove heat from its surroundings (Figure 7.2). Fans are usually necessary to circulate the storage air over the cooling coils of the evaporator and through the stacks of produce in the store. The main agent for the transfer of heat from the interior of the store to the cooling coils is air movement, although radiation and convection may play a small part.

The removal of heat from the circulating air in a cool room by the evaporator coils is referred to as the 'direct expansion system'. The 'indirect expansion system' is a variation in which a liquid, usually a mixture of polyethylene glycol and water with a low freezing point, is cooled and the cold solution is

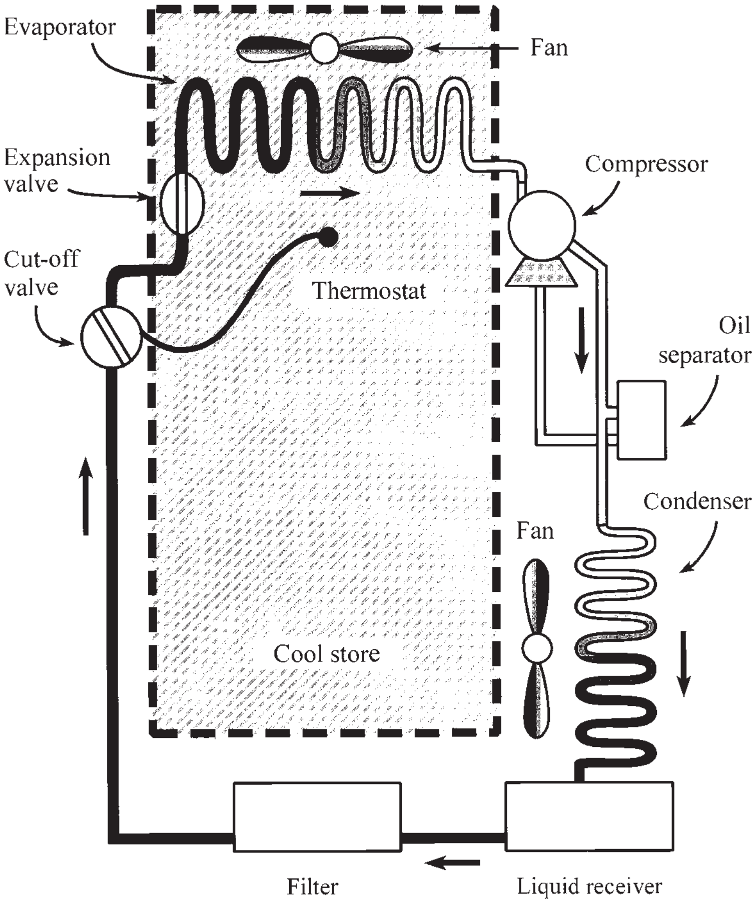


Figure 7.2 **Basic component parts of mechanical refrigeration plant.** The part of the cycle from the compressor to the thermal expansion valve operates under high pressure to enable condensation of the hot gaseous refrigerant. The evaporator coils operate at low pressure to enable the refrigerant to boil. The condenser may be either air or water cooled.

circulated through the cooling coils in the cool room. The reservoir of cold polyethylene glycol solution can buffer periods of high cooling demand during the day when warm produce is being loaded. Inevitably, the surface temperature of the cooling coils must be lower than that of produce to ensure that heat from all sources in a cool room is removed and produce remains at a constant temperature. This temperature gradient is accompanied by a gradient in vapour pressure (vapour pressure deficit, VPD) between the produce and the evaporator coils. This VPD enhances water loss from produce. For produce with high transpiration rates (e.g. leafy vegetables) a preferred system is to cool and humidify the room air by passing it through a shower of cold water, which has been cooled by mechanical refrigeration. This indirect expansion system provides air at 1–2°C and greater than 98% RH.

Design and construction of cool stores

The essential features of cool rooms are good insulation, a high cooling capacity with close control of temperature, and RH of greater than 90%. A common minimum design criterion is to provide capacity to cool a daily intake of 10% of the capacity of the store at an initial rate of not less than 0.5°C per hour. Such a capacity requires 1 tonne (3.5 kW) of refrigeration capacity per 18 tonnes of produce for small stores of up to about 150 tonnes capacity, and about 1 tonne per 25 tonnes for larger stores. The capacity for larger stores can be varied by having two or more compressors or by the technique of cylinder unloading in one compressor.

Accurate temperature control generally requires variation of no more than ±1°C and a variation in time in any one position of no more than +0.5°C. A temperature difference of 1°C over the storage period has significant effects on most produce, especially those stored at less than 5°C. The optimum thickness of insulation in walls and ceiling needs to keep the overall heat transfer to about 0.3 kJ/m^2/h. This gives an economical ratio of cost of refrigeration capacity to cost of insulation and also enables a high humidity to be maintained. The best insulation is the cheapest that gives the required performance.

Cool stores may be constructed in many ways, and provided that the above conditions are met, all can be satisfactory. Many cool rooms are either of sandwich panel construction with polystyrene foam slabs as the insulation in the prefabricated panels, or foamed-in-place polyurethane is applied to the inner faces of the structure. The 'skins' on the outsides of the insulation are metal, commonly aluminium or zinc-coated steel (Figure 7.3). Floors are constructed of reinforced concrete capable of carrying point loads from forklifts as well as

Figure 7.3 **A modern cool room being constructed using metal-clad panels insulated with polystyrene.** A Colorbond® finish has been applied to the panels to facilitate cleaning. All joints and entry points for electrical cables and plumbing are sealed with waterproof silicone mastic to prevent water entering the insulation.

Figure 7.4 **A cool room in which the air is blown through the coils by fans mounted at the back of the coils (forced draft cooling).** The more common arrangement is to mount the fans in front of the coils (induced draft cooling), which gives better air distribution. In this example, the palletised produce is placed on racks.

stacking loads. Cooled air is generally supplied by forced or induced draft coolers (FDCs or IDCs) (Figure 7.4), consisting of framed, closely spaced, finned, cooling coils fitted with fans to circulate the air over the coils. Some means of defrosting the coils is also required when storage temperatures are low and the coil surface operates at temperatures below 0°C.

Controlled atmosphere cool stores

Large-scale long-term CA storage at low temperatures is widely used for commodities such as apples and pears. The principles and history of CA storage were discussed in Chapter 6 – this section deals with the specific construction and design needs of modern low-temperature CA stores.

Many CA stores now employ gas separators such as the pressure swing adsorption (Figure 7.5) or hollow-fibre membrane systems (Figure 7.6) that can generate gas streams containing low oxygen concentrations by separating oxygen and nitrogen from the air. Oxygen concentrations can be reduced rapidly by flushing the cool room and once the required oxygen levels are reached, carbon dioxide concentrations are controlled by scrubbing with activated charcoal adsorbers that are also operated in a pressure swing mode. These carbon dioxide scrubbers have replaced the more cumbersome system of using hydrated lime in paper sacks. The operation of low-oxygen stores is relatively simple and is frequently automated. Despite these advances, it is imperative to build gas-tight stores to ensure that separators are used economically. These land-based systems for generating and maintaining CA have been adapted to ship refrigerated holds and to refrigerate shipping containers.

An essential feature of a CA store is the provision of an

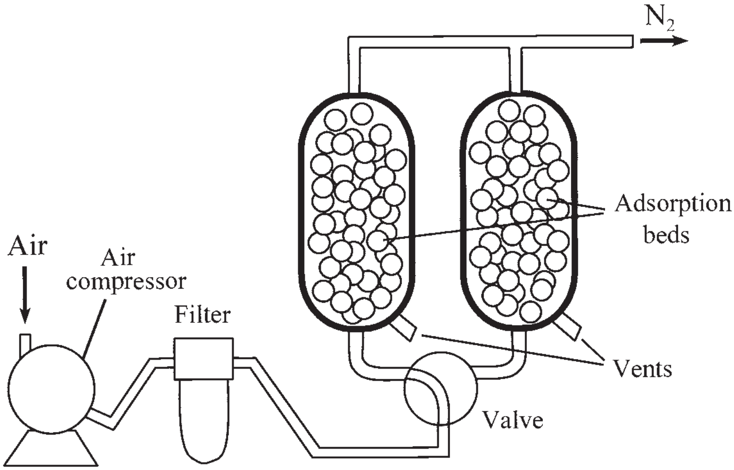


Figure 7.5 Pressure swing adsorption machine. Filtered dry compressed air is passed alternately through two chambers packed with molecular sieves that retain oxygen when under high pressure and allow compressed nitrogen of at least 99% purity to be generated. When the adsorption capacity in one chamber is nearly reached, the compressed air is automatically switched to the second chamber and the first is purged at atmospheric pressure to release the adsorbed oxygen.

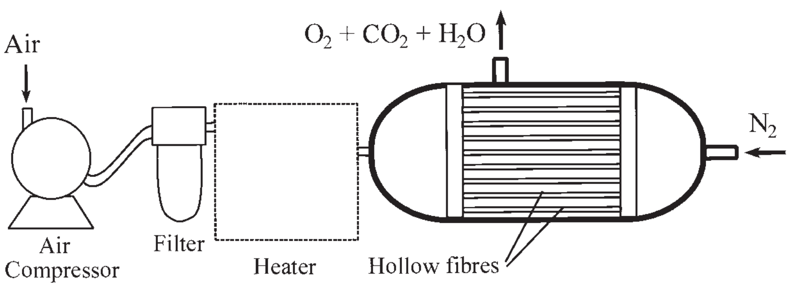


Figure 7.6 Hollow-fibre membrane system. High-pressure dry, oil-free air is passed through hollow fibres constructed from a polymer that is differentially permeable to gases. Oxygen, carbon dioxide and ethylene permeate the fibres rapidly and are purged to the atmosphere, enabling the generation of a high-pressure stream containing up to 99.5% nitrogen.

effective gas barrier, which is most conveniently placed directly on the inside of the insulated surface. This not only maintains tight CA control but also prevents moisture penetrating this barrier – moisture can lead to waterlogging and destruction of the insulation. Application of foamed-in-place polyurethane enables the satisfactory conversion of existing cool stores to CA and also provides a cheap method of construction by completely lining the interior of a simple metal chamber. If correctly applied, the polyurethane provides both insulation and a gas barrier. A pressure relief device (burp valve), usually a water trap, fitted through the walls of such a rigid, gas-tight structure is essential to avoid damage by limiting pressure differentials to 370 Pa (15 mm water gauge). Gas-tight rooms are also essential for postharvest gas treatment with 1-MCP (Chapter 6).

While CA suppresses fruit and vegetable metabolism to maintain quality, these atmosphere levels are hazardous to humans. CA stores should be treated with respect to ensure that no one is ever exposed to such an atmosphere unless properly trained and wearing an efficient respirator with its own oxygen supply. It is also critical to ensure that CA stores are well ventilated before entry.

Management of produce for storage

High quality produce will come out of storage only if it is of high quality on entering the store, and if management of the storage facilities is of a high standard. Poor quality fruit will not improve with storage. Given correct selection and handling of produce, the success of subsequent storage depends on quickly reducing the temperature of produce to the desired level and maintaining the temperature with little variation, close monitoring and maintenance of the desired humidity and gas concentrations in the storage atmosphere, and avoiding excessive storage.

Precooling the rooms before storage

It is important to reduce the temperature of the storage room down to the appropriate temperature a few days before commencement of intake of produce. Three days is enough for a fully insulated room, but rooms without floor insulation should be precooled for a week to ensure that the floor has cooled down to equilibrium before loading. Failure to precool the room before loading is often the cause of unsatisfactory maintenance of temperature, slow cooling and excessive shrinkage of produce.

Pre-storage selection and sorting of produce

It is desirable to sort and size-grade produce before storage. Not all harvested produce is fit for storage. Some items have better keeping qualities than others, some are blemished but may be suitable for processing into fresh-cut or other products, and some is unmarketable. Refrigerated storage is expensive, and it is not economic to have produce which is not fit for sale or produce which would be better marketed immediately occupying cool storage space.

Temperature control

Air movement transfers heat from the produce to the coils by natural convectional circulation in a room with overhead grids (cooling pipes); by forced circulation in rooms cooled by forced or induced draft coolers; or by a combination of natural and forced convection. It follows that the nature of the packages and the method of stacking must allow the air to move readily through all parts of the stack for the produce to be cooled quickly and uniformly.

Several factors influence the spatial distribution of temperature in a store to ensure the variation in temperature does not exceed ±1°C. The most important single requirement for uniform produce temperatures is uniform distribution of the cooling air over the entire area on the top of the stack. This applies equally to the distribution of air from fan-driven air circulation systems and to the even distribution of the coils over the ceiling in natural circulation rooms. Also of importance is the uniformity of the air paths through a stack of packages of produce (or *stow*), as air always takes the path of least resistance. Ideally, there should be a continuous narrow air slot in the direction of air flow past at least two faces of every box or carton and each side of every bulk bin, together with no large vertical gaps in the stack to allow short-circuiting by the cool air. The room should be well insulated to reduce heat leakage, and the coolers should have ample capacity to ensure a small difference between the temperature of the air and coil surface.

Loading

If possible, warm produce should be cooled in a separate cool room from that used for storage. If only one room is available, the designated daily intake (commonly 10% of capacity) should not be exceeded. Otherwise, the storage life of produce will be reduced and shrinkage promoted. Warm produce should be loose stacked, and cooling can be improved with the aid of an auxiliary portable fan placed in front of the stack, with the suction side to the produce, to draw air through the stack. More rapid cooling methods (such as forced air cooling and hydrocooling) should be used for highly perishable produce (Chapter 4).

Stacking

Cool rooms should not be overfilled as this results in variable temperatures and therefore a poor out-turn of produce. Packaged produce should be carefully stacked to give economy of space, adequate and uniform air circulation, and accessibility. This requirement is facilitated when the boxes of produce are unitised on pallets for mechanical handling. The following requirements for stacking are essential for rapid cooling and good temperature control for any type of package:

- Keep the stack 8 cm away from outer walls and 10–12 cm away from any wall exposed to the sun. This will ensure that heat coming in through the walls will be carried away to the coils by air moving freely between the stack and the wall without warming nearby produce.
- Leave a clear air space between the top of the stack (the load line) and the ceiling of more than 25 cm. This allows the free flow of air from the forced draft cooler and ensures that a uniform layer of cold air blankets the whole stack. The full depth of the space in front of a forced draft cooler should be kept clear for a distance of 2 metres to allow it to function properly and to avoid freezing produce.

- An air plenum (gap) of about 8 cm is required between the floor and the stack. When bins and pallets of boxes are used, the pallet bases provide the necessary air gap above the floor. Wherever possible, they are placed with the pallet bases parallel to the direction of air flow (i.e. running towards the forced draft cooler).
- When boxes or cartons without vents are used, leave small, vertical air paths within the stack not less than 1 cm wide between adjacent packages since heat exchange takes place mainly at the surface of the packages. A layer-reversed, open chimney stacking pattern will provide the necessary vertical gaps between cartons (1 cm) and at the same time provide a stable stack. Bulk storage bins that may contain 200–500 kg of produce should have air gaps in the floor of 8–10% of the base area. Rapid cooling of produce is possible in such bins in standard cool rooms. Bins of warm produce should be first stacked only two-high overnight to allow quick removal of field heat from the produce. Next day, they may be stacked to full height. Unless a high humidity is maintained in the cool store, produce in bins that also have air gaps in the side may shrivel excessively. The sides of the bins can be lined to reduce shrivel, but cooling will be slow if the gaps in the floor are covered.

Weight loss and shrinkage

Excessive shrinkage is caused by many factors including placing hot produce in the cool store, packing produce into dry wooden boxes or cartons into cool stores, low humidity due to poor insulation or cooling, slow cooling, and excessive air circulation. Fast cooling, uniformly low temperatures and high humidity in the store are therefore necessary for low weight loss. The extra cost of additional cooling and insulation and an effective vapour barrier are more than offset by reduced weight-loss and better produce condition after storage.

Weight loss during cooling may also be greatly reduced by wetting warm produce such as leafy vegetables with potable water before it is put into the store. It is preferable to harvest produce early in the morning, when it is coolest, and put it directly into the cool store. This reduces the load on the refrigeration plant and lowers costs. When it is necessary to harvest produce later in the day in hot, dry weather, it may be practicable to spray some types of produce with potable water, to leave produce overnight in the open to cool by a combination of evaporative cooling and radiation cooling (if the night sky is clear), and place into store the next morning.

Orderly marketing and over-storage

Over-storage remains a common fault in the cool storage of produce. It is sound marketing practice to commence selling long-keeping produce such as apples and pears from the cool store early and to continue regularly throughout the season. To achieve orderly marketing, produce in the cool store needs to be segregated according to the expected eating and keeping quality and removed for sale accordingly; as a general rule produce first in should be first out. It should be remembered that retaining eating quality and providing consumer satisfaction are the drivers for storage. This is discussed more in Chapter 10.

Over-storage and other storage problems may be minimised by transferring small samples of produce to room temperature at intervals during storage and at the first sign of deterioration of the sample, the whole line should be marketed without delay. Regular inspection of samples during storage is imperative for fruit such as apples or stone fruits, which may look in perfect condition in the cool store but either develop physiological disorders or fail to ripen satisfactorily after removal to ambient temperature.

Sanitation

Cool rooms should be thoroughly cleaned during and at the end of each season to reduce the risk of losses by decay. The walls and floor can be a source of fungal contamination and should be regularly washed with sanitisers such as a solution of sodium hypochlorite (chlorine). Mouldy or otherwise contaminated harvest and storage bins and boxes should also be thoroughly cleaned and sanitised before reuse. Cleaning of boxes and bins has been made easier by the gradual replacement of wooden bins and boxes with plastic bins with smooth surfaces.

Grading machines are a common source of mould contamination that leads to the development of rots in storage. These machines should be cleaned and swabbed or sprayed with a sanitiser solution daily. The equipment should be regularly inspected for defects and any points likely to cause produce injury should be repaired.

A range of sanitising options are available, including ozone. Installation of ozone generators has been found to keep cool rooms free of surface moulds and reduce the spread of fungal spores. However, ozone is toxic to humans and health regulations limit daily exposure of healthy individuals to a maximum of 0.3 μL/L for not more than one hour consisting of four sessions of not more than 15 minutes each. Individuals should not be be exposed repeatedly to 0.1 μL/L during an 8-hour working day. Concentrations of ozone that people can smell are greater than this concentration.

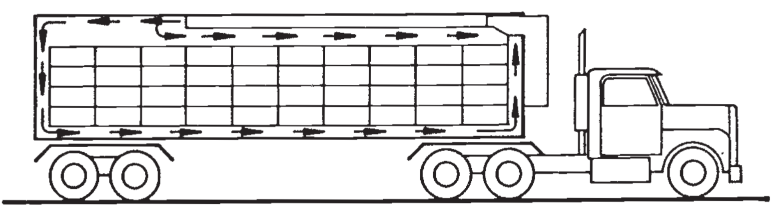
Refrigerated transport

Much produce is transported over long distances under refrigeration on land and sea. Refrigerated road, shipping or rail vehicles can be regarded as insulated boxes fitted with modular mechanical refrigeration units driven by electric or diesel motors. Refrigerated ships have a central refrigerating plant; the whole ('reefer ships') or only part of the carrying space on a vessel may be insulated and refrigerated.

Much refrigerated sea freight is carried in 20 or 40 foot shipping containers (with 30 or 60 cubic metres capacity), which permit temperature control from the packing house to the market. Most refrigerated freight containers have their own electrical refrigeration unit (integral containers) (Figure 7.7), but they are not designed for rapid cooling so that successful refrigerated transport requires thorough precooling of the load. However, much produce is currently loaded into containers without precooling. Respiratory heat is a significant proportion of the refrigeration load, consequently some air space must be provided between the packages during stowage of produce unless the journey is short. Significant amounts of heat enter refrigerated road transport vehicles from solar radiation, heat reflected from the road and from air leakage through the doors. To ensure the maintenance of even temperatures, it is

Figure 7.7 Insulated shipping container fitted with a built-in refrigeration unit

Figure 7.8 To ensure effective air circulation in a refrigerated road vehicle, there must be an air delivery chute, ribs on the doors and walls, channels or pallets on the floor and a return bulkhead



SOURCE A.K. Sharp, A.R. Irving and A.A. Beattie (1985) 'Transporting fresh produce in refrigerated trucks', Agfact, H1.4.3, NSW Department of Agriculture, Sydney.

necessary to provide a good circulation of cooling air around the load (Figure 7.8). Rules covering precooling, stowage, and air circulation have been developed from research and commercial experience; maximum acceptable loading temperatures are commonly specified and should be closely policed.

There is a range of commercial controlled atmosphere shipping containers, which can either actively or passively regulate the concentration of oxygen and carbon dioxide inside the refrigerated container during transport. In both cases, the levels of oxygen and carbon dioxide need to be closely monitored with sensors. It is important that these sensors are calibrated and work as described.

Passive regulation of the atmosphere within a container involves the opening of the fresh air vents on the container. This technology takes advantage of natural respiration of the produce inside the container to generate the required atmosphere levels. Active modification of the shipping container atmosphere can be made with the direct injection of suitable gas mixes in combination with vent regulation. Further developments with the addition of ozone into shipping containers are also available.

Measurement of the storage environment

The successful use of storage technology depends on accurate and reliable monitoring to establish and maintain the desired environmental conditions in the storage chamber. This will certainly involve the measurement of temperature and possibly also RH, ethylene, carbon dioxide and oxygen.

Temperature

A wide range of devices can be used to measure temperature. Digital thermometers use an electronic circuit to detect the output of a thermocouple or thermistor that is converted to a temperature on a digital display. Digital data loggers are an extension of the digital thermometer and measure temperature at pre-set intervals of time, with the data stored in a solid-state memory for later recall and analysis. Data can also be sent wirelessly to computer terminals. Real-time temperature monitoring and control over mobile phone networks is also used. Remote temperature recording can also be achieved with thermocouples, which are two strips of different metals joined together at each end. When the junctions are at different temperatures, an electromotive force develops that is proportional to the difference in temperature.

Resistance thermometers based on a thermistor operate similarly – they are robust, which allows use for permanent distant reading installations; for example, in refrigerated ships. Older thermometers such as liquid-in-glass thermometers are still valuable. Fluid-filled dial thermometers, consisting of a sensing bulb connected to a spiral tube filled with a fluid, can take measurements at a distance of up to a few metres. These are often used as externally indicating, dial thermometers in cool stores.

All temperature-measuring devices need to be calibrated; it should never be assumed that readouts are accurate. While it is impressive that temperatures on a digital thermometer can be displayed to a tenth of a degree, this can give operators the misleading impression that the data are correct. The accuracy of every device should be checked at 0°C with an ice-water mixture or against a pre-calibrated thermometer near the temperature at which it is to be used. Alternatively, the device may be submitted to an approved testing laboratory for calibration. The accuracy of hand-held devices used in the field should also be checked frequently.

In addition, the placement of temperature measuring devices in cool stores and similar structures is critically important. The nature of any refrigeration system means there is always a gradient in temperature within the chamber. The aim is to maintain the bulk of the produce at the recommended storage temperature, without freezing or over-cooling the coldest part. A device that is to be used as a thermostatic control for a forced draft cooler is best placed in the air coming off the cooler, and the thermostat adjusted to give the minimum acceptable temperature. The temperature of produce in a cool store should be measured in several positions due to the spatial variations in the chamber. Air temperatures just inside the door never give accurate readings of produce temperature.

Relative humidity

RH is not as easy to measure as temperature. In Chapter 5 it was noted that there are various ways of defining the amount of water in air. Thus, many methods have been devised for measurement of atmospheric water status and for the most part, no one hygrometer (or psychrometer) is suitable for all purposes over the full range of humidity and temperature.

Electric hygrometers operate by recording variations in the resistance, capacitance or some other electrical parameter of a sensor with changing water sorption or desorption. Electrodes are attached to an insulating base containing a thin layer of an electrolyte which equilibrates with the surrounding air. This data can be recorded, logged and remotely sent.

A wet-and-dry bulb hygrometer is the simplest and was once the most widely used instrument for measuring RH. It consists of two thermometers, one of which, the dry bulb, measures the air temperature. The neighbouring wet bulb thermometer has a wet wick around the bulb and evaporation of water from the wick into the atmosphere results in it being cooled. The temperature difference between thermometers can be translated to per cent of RH, water vapour pressure or dew point using tables prepared for this purpose.

The calibration of most electronic RH measuring devices should be checked over saturated inorganic salt solutions. Precise relationships between headspace RH over a variety of saturated inorganic salt solutions are published in reference handbooks.

Gas analysis

Carbon dioxide, oxygen and ethylene can be measured by physical methods such as gas chromatography and the use of sensors. In the laboratory, thermal conductivity gas chromatography is commonly used for analysis of carbon dioxide and oxygen. An alternative method for rapid analyses that is widely used by industry, particularly for monitoring controlled atmosphere storage rooms, is an infra-red gas analyser for carbon dioxide connected in series with a paramagnetic oxygen analyser. These properties of the respiratory gases have been utilised for the generation of a wide range of portable hand-held analysers that are now commercially available to analyse for these gases. In addition, low-cost sensors have also been developed and are widely used.

Similarly, ethylene determination in the laboratory is generally conducted with flame ionisation gas chromatography.

But a range of sensors such as photoionisation detectors has generated portable instruments that are rapid in operation. However, the limit of detection of sensors may be too high in the light of current thinking on threshold levels of ethylene (Chapter 6). Portable analysers need to be calibrated with a certified gas mixture. This should be performed even when the device contains an internal calibration system.

8
Physiological disorders

Physiological disorders involve the breakdown of plant tissue that is not directly caused either by pests and diseases or by mechanical damage. There are literally hundreds of described disorders and injuries in fruit and vegetables. The names and classification of these disorders are very descriptive and reflect their often indeterminent and seasonal nature. Many low temperature disorders were named by cool store operators and shipping agents to describe the variety of browning conditions that developed on or in fruit held at low temperatures. The biochemical and biophysical mechanisms that give rise to physiological disorders are extremely complex and not well understood. While the description of most disorders might be considered non-scientific, it has nonetheless been an important step towards optimising postharvest storage and handling practices.

Physiological disorders may develop in response to various preharvest growing and postharvest storage conditions such as nutrient deficiency that occurs in the field and low temperature stress during storage. Indeed, many of the pre- and postharvest factors interact leading to very complex interactions and expressions of physiological disorders (Figure 8.1). The effect of the preharvest growing environment on the development of many disorders cannot be overstated.

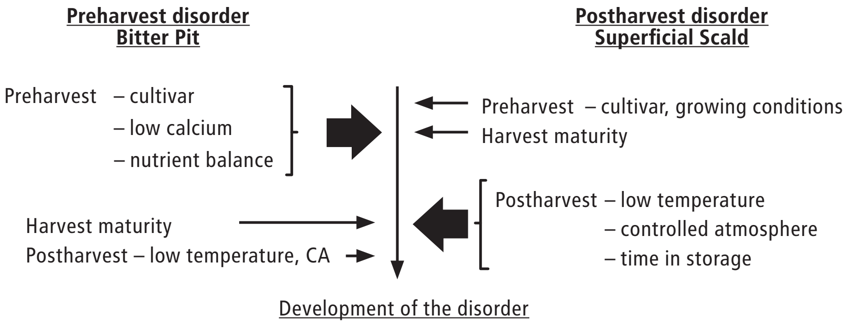


Figure 8.1 **Development of two physiological disorders in apples.** Pre- and postharvest factors such as cultivar, growing conditions, harvest maturity and storage conditions interact to affect the incidence and severity of each disorder. Bitter pit is primarily related to preharvest factors while superficial scald is primarily a postharvest-related physiological disorder.

Physiological disorders can be divided into five general categories: (1) nutritional, (2) temperature related (low and high), (3) respiratory, (4) senescence and (5) miscellaneous. Nutritional and low temperature disorders are particularly common but problematical and are considered in more detail below. Sunburn on the shoulders of fruits, such as tomatoes and mangoes, is a common example of high temperature injury that occurs in the field prior to harvest. Respiratory disorders are commonly associated with low oxygen and/or high carbon dioxide concentrations in modified atmosphere storage. Black heart of potatoes is an example of low-oxygen injury and midrib browning of lettuce is an example of high carbon dioxide injury. Senescence disorders, such as mealiness in apples, are generally associated with harvest of overmature produce and/or over-storage of produce. Miscellaneous disorders are generally produce-specific in terms of the relatively unique symptoms expressed. For instance, exposure to ethylene during storage can cause russet spotting on the midrib of lettuce leaves and bitterness arising from isocoumarin accumulation in stored carrots. Greening of potatoes exposed to light and rooting of onions exposed to high humidity may also be considered miscellaneous physiological disorders.

In diagnosing causes of physiological disorders or attempting to predict the likelihood of symptom expression in harvested produce, the following parameters may need to be taken into account: preharvest growing environment (e.g. temperature, nutrition and water regimes), crop development factors (e.g. yield or crop load, position on the plant, and carbohydrate, water and/or nutrient partitioning), and postharvest storage conditions (e.g. temperature regime, gas atmosphere and storage time). All of these factors can interact to affect the development of physiological disorders.

A feature of many physiological disorders is that they do not express themselves at harvest and only appear after storage or when in the hands of the consumer. This is disconcerting to the producer as considerable time and expense has been invested in growing, handling and storing produce that appears to be of good quality only to discover disorder symptoms during or after storage. There can be ongoing losses as consumer dissatisfaction on encountering physiological disorders results in a poor eating experience and reduces the likelihood of future sales. However, many physiological disorders can now be successfully managed and fewer disorders are seen in the marketplace, though new disorders are continually being discovered and old disorders rediscovered with the introduction of new cultivars and storage technologies. For example, soft scald in apples was virtually eliminated by growing less susceptible cultivars, but new cultivars with superior market and eating characteristics were subsequently found to be highly susceptible to soft scald. Furthermore, newly developed cultivars which are now widely grown, such as Honey Gold mango, have new storage disorders with names such as 'under skin browning'. In addition, new storage technologies such as 1-MCP and ultra-low oxygen storage have exacerbated some storage disorders.

Mineral deficiency disorders

Disorders associated with mineral deficiencies and whose symptoms are sometimes expressed only after harvest in fruits may be prevented by the addition of the specific mineral element either during growth or after harvest. However, for most mineral deficiency disorders the actual role of the mineral in preventing the disorder has not been well established and there are often interactions with other minerals and growing conditions which affect development of the disorder.

Calcium

Calcium is associated with more postharvest-related deficiency disorders than any other mineral (Table 8.1). Calcium is an essential element that binds with pectic substances in the middle lamella and with cell membranes. Added calcium may possibly prevent some disorders by strengthening these cell structural components, without alleviating the original causes of the disorder. Strengthening of cell components could prevent or delay the loss of sub-cellular compartmentation and the associated chemical and enzyme-mediated reactions that cause browning symptoms. Calcium has also been shown to affect the activity of many enzyme systems and metabolic sequences in plant tissues.

Table 8.1 Some calcium-related disorders of fruit and vegetables

Produce	Disorder
Apple	Bitter pit, lenticel blotch, cracking, internal breakdown, water core
Avocado	End spot
Bean	Hypocotyl necrosis
Brussels sprout	Internal browning
Chinese cabbage	Internal tipburn
Carrot	Cavity spot, cracking
Celery	Black heart
Cherry	Cracking
Escarole	Brown heart, tipburn
Lettuce	Tipburn
Mango	Soft nose
Parsnip	Cavity spot
Pear	Cork spot
Pepper	Blossom-end rot
Potato	Sprout failure, tipburn
Tomato	Blossom-end rot, blackseed, cracking
Watermelon	Blossom-end rot

A classic calcium-related physiological disorder is bitter pit in apples, which illustrates the interactions of a range of pre- and postharvest factors that affect the expression of the disorder. The first symptoms of bitter pit appear in apple flesh tissue, and as the disorder progresses external blemishes develop on the skin. Badly affected flesh often has a bitter taste, hence the name 'bitter pit'. Small bruise-like spots, which may be darker than the surrounding tissue, develop on the skin and become brown and sunken to form sunken pits that dry out to become tough and spongy (Plate 1B). Spots usually develop first at the calyx end of the fruit, but highly susceptible cultivars can be damaged up to the shoulder. Typical of many physiological disorders, even fruit with no obvious symptoms at harvest can develop skin pitting in storage.

Bitter pit can occur on fruit in trees where the tree may have an adequate level of calcium but the fruit may be deficient. Calcium moves from the roots into the xylem and is carried to areas such as the leaves where transpiration occurs. It moves slowly into other parts of the plant such as the fruit. Bitter pit results when there is competition between leaves and fruit for calcium. Thus, calcium uptake can be influenced by several orchard factors such as water availability, climatic factors, nutrition, tree vigour and crop regulation – good tree management is critical to avoid bitter pit. Postharvest calcium dips can be used but their efficacy is variable where the extent of control is related to the amount of calcium taken up by the fruit. Vacuum infiltration of calcium solutions was nationally adopted in New Zealand in the 1980s and successfully eliminated the disorder in the leading export cultivar, Cox's Orange Pippin.

Another common calcium deficiency disorder is blossom-end rot of tomatoes, but this can be readily managed by the application of calcium salts as a preharvest spray.

Other minerals

Boron deficiency in apples can lead to a condition known as internal cork. This condition is marked by pitting of the flesh and is often indistinguishable from bitter pit and highlights the complexities of the different physiological disorders. The differences between the two disorders are that internal cork is prevented by the application of boron sprays while bitter pit responds to calcium treatment. Another difference is that internal cork develops only on the tree while the bitter pit can develop after harvest.

The major mineral in plants is potassium and both high and low levels of potassium have been associated with abnormal metabolism. High potassium has been associated with the development of bitter pit in apples, so both high potassium and low calcium are correlated with pit development. Low potassium is associated with changes in ripening tomatoes and delays the development of full red colour by inhibiting lycopene biosynthesis.

Low temperature disorders

Storage of fruit and vegetables at low temperature is generally beneficial, as the overall rate of metabolism is lowered and therefore produce quality is maintained (Chapter 4). However, low storage temperatures do not suppress all cellular processes to the same extent. Some reaction systems are especially sensitive to low temperature and cease to function below a critical temperature. A number of cold-sensitive enzyme systems have been identified in plant tissues. Cold temperatures in such produce lead to a metabolic imbalance with the accumulation of some reaction products and a shortage of related reactants. If the imbalance becomes serious, essential substrates may not be produced and/or toxic products can accumulate. Consequently, cells will lose their function and structure. Damaged cells often appear as discoloured (e.g. brown or black) areas (Plate 1C and Figure 8.2). Metabolic disturbances occurring at sub-ambient

Figure 8.2 **Chilling injury in avocado fruit appears as browning of the mesocarp due to the breakdown of cell compartmentation and the action of polyphenol oxidases to produce tannins (left).** The fruit was stored in air for 21 days at 5°C and then ripened at 20°C for five days. The fruit on the right remained free of symptoms after ripening in air at 20°C following storage for 21 days at 5°C in sealed polyethylene bags that generated atmospheres typically comprising 7% carbon dioxide, 3% oxygen and 90% nitrogen.

SOURCE K.J. Scott and G.R. Chaplin (1978) 'Reduction of chilling injury in avocados stored in sealed polyethylene bags', *Journal of Tropical Agriculture (Trinidad)* 55: 87–90. (Used with permission.)

temperature are generally divided into chilling injury and low temperature-associated physiological disorders.

Chilling injury

Chilling injury is characterised by well-defined symptoms that are readily and reproducibly expressed in damaged tissues as a consequence of exposure to low temperature (Table 8.2). Chilling injury typically results from exposure of susceptible produce, especially that of tropical or subtropical origin, to temperatures below 10–15°C. However, the critical temperature at which chilling injury occurs varies greatly among commodities. Chilling injury is different to freezing injury, which results from the formation of ice crystals in plant tissues at temperatures below their freezing point. Both susceptibility to and symptoms of chilling injury are produce- and even cultivar-specific. Moreover, the same commodity grown in different areas may behave differently in response to similar temperature conditions.

Skin pitting is a common chilling injury symptom that occurs due to the collapse of cells beneath the skin surface. The pits are often discoloured where high rates of water loss from damaged areas may occur and lead to larger and darker symptoms. Browning or blackening of flesh tissue is another common feature of chilling injury (e.g. avocado; Figure 8.2). Chilling-induced browning in fruit typically appears first around the vascular (transport) strands. Fruit that has been picked immature may fail to ripen or will ripen unevenly or slowly after chilling (e.g. tomato). Water-soaking of leafy vegetables and some fruits (e.g. papaya) is also often observed. Symptoms of chilling injury normally occur while the produce is at low temperature but sometimes only appear when the produce is moved to a higher temperature, where deterioration may then be quite rapid, often within a matter of hours.

Chilling injury causes the release of metabolites (e.g. amino acids, sugars) and mineral salts from the damaged cells. This leakage of metabolites and ions, together with the degradation of cell membranes, provide substrates for growth of pathogenic organisms, especially fungi. Such pathogens are often present as latent infections or may contaminate produce during harvesting and postharvest handling. Thus, an increased incidence and severity of rots is another common symptom of chilling injury (Plate 1A), particularly upon removal from low temperature storage. The development of off-flavours or odours is another consequence of chilling injury.

The temperatures reported in Table 8.2 are limiting or critical temperatures below which symptoms of chilling injury will

Table 8.2 Chilling injury symptoms of some fruits and vegetables

Produce	Lowest safe storage temperature (°C)	Chilling symptoms
Avocado	5–12*	Pitting, browning of pulp and vascular strands
Banana	12	Brown streaking on skin
Cucumber	7	Dark coloured, water-soaked areas
Eggplant	7	Surface scald
Lemon	10	Pitting of flavedo, membrane staining, red blotches
Lime	7	Pitting
Mango	5–12	Dull skin, brown areas
Melon	7–l0	Pitting, surface rots
Papaya	7–15	Pitting, water-soaked areas
Pineapple	6–15	Brown or black flesh
Tomato	10–12	Pitting, *Alternaria* rots

*A range of temperature indicates variability between cultivars in their susceptibility to chilling injury.

generally be observed. Highly chilling sensitive organs, such as bananas and pineapples, have relatively high critical temperatures of 12°C or higher. It has even been suggested that some pineapple cultivars have a critical temperature greater than 20°C. Symptoms of chilling injury, particularly those that become evident upon return to ambient conditions, are often more severe the further the temperature is below the critical chilling temperature.

The safest method for management of chilling injury is to not expose the commodity to temperatures below the threshold temperature. However, it has been found that exposure for only a short period to chilling temperatures, with subsequent storage at higher temperatures, can be tolerated. This conditioning process has been found to be effective for managing black heart in pineapples, woolliness in peaches, and flesh browning in plums. Modified atmosphere storage may also reduce chilling injury in some commodities. Finally, maintenance of high humidity both in storage at low temperature and after storage can minimise the expression of chilling injury symptoms, particularly pitting.

The cellular events of chilling injury can be separated into primary and secondary events. Primary events are virtually immediate and largely reversible (Figure 8.3). Secondary events are transiently reversible but become irreversible with the onset of cell death and tissue necrosis. The main primary event in chilling injury development has been ascribed as a change in the physical state of membrane lipids/proteins (i.e. membrane phase change), which leads to changes in the properties of cell membranes. Consequently, ion and metabolite movement across affected membranes and also the activity of membrane-bound enzymes are disrupted. The overall

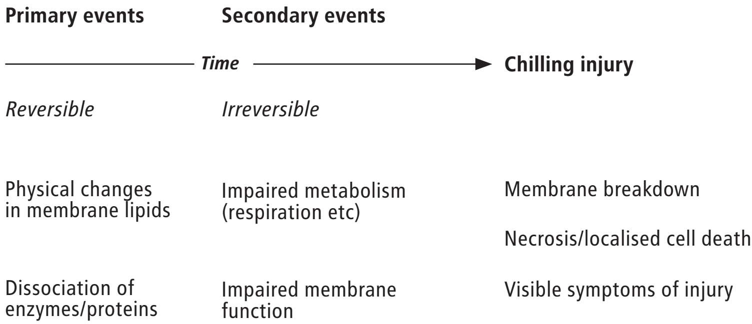


Figure 8.3 Time sequence of events in response to exposure to chilling temperatures leading to chilling injury

consequence of membrane disturbance is the breakdown of sub-cellular compartmentation, which is readily measured as increased ion leakage from chill-injured tissues. Browning symptoms can result from the mixing of the polyphenoloxidase (PPO) enzyme with phenolic compounds released from the vacuole of chilled membranes. Other events include the production of reactive oxygen species (e.g. hydrogen peroxide) that oxidise and thereby damage sub-cellular constituents including membranes, and dissociation of enzymes and other proteins into their structural sub-units such that enzyme activities are altered and structural proteins (e.g. tubulin) are disrupted. In addition, the accumulation of toxic compounds (e.g. acetaldehyde) may accompany imbalanced metabolism.

Low temperature-associated physiological disorders

Low temperature-associated physiological disorders affect a range of fruit and vegetables but are particularly well described for deciduous tree crops such as apples and peaches and for citrus fruits. These physiological disorders tend to be expressed in discrete areas of tissue – some disorders affect the skin of produce but leave the underlying flesh intact, while others only affect certain areas of the flesh or the core. Low temperature disorders may be considered as a type of chilling injury that have developed slowly under low temperature storage conditions.

Apples have been studied more intensely than any other commodity, which perhaps explains why they have the greatest variety of described physiological disorders (Table 8.3). When more research effort is devoted to other fruits, the list of physiological disorders will undoubtedly increase (Table 8.4). There is no reason to believe that apples should be more prone to develop physiological disorders than other commodities.

Table 8.3 Some physiological disorders of apples

Disorder	Symptoms
Superficial scald	Slightly sunken skin discolouration; may affect whole fruit
Sunburn scald	Brown to black colour on areas damaged by sunlight during growth
Senescent breakdown	Brown, mealy flesh; occurs with over-mature, over-stored fruit
Low temperature breakdown	Browning in cortex
Soft (or deep) scald	Soft, sunken, brown to black, sharply defined areas on the surface and extending a short distance into the flesh
Core flush (brown core)	Browning within core line
Water core	Translucent areas in flesh; may brown in storage
Brown heart	Sharply defined brown areas in flesh; may develop cavities

Table 8.4 Physiological disorders of other fruit and vegetables

Produce	Disorder	Symptom
Celery	Pithiness	Breakdown of the internal pith parenchyma tissues of the petiole
Citrus	Granulation	Gel formation within juice vesicles that reduces extractable juice
Date	Blacknose (sugar tip)	Severe checking of the skin
Garlic	Waxy breakdown	Clove becomes translucent, sticky and waxy but the outer dry skins are not affected
Grape	Shatter	Loss of berries from the stem
Mango	Internal flesh breakdown (stem-end cavity)	Flesh breakdown and development of internal cavities between seed and peduncle
Onion	Watery scales	Thick, leathery skin with watery, glassy, fleshy scales below
Peach	Woolliness	Red to brown, dry areas in flesh
Pineapple	Flesh translucency	Flesh translucency
Plum	Gel breakdown	Brown, gelatinous areas on skin and flesh breakdown
Potato	Black heart	Dark grey to black tissue in centre of tuber
Sweet potato	Pithiness	Spongy tissue
Turnip	Brown heart	Brown internal tissue

Various temperature management programs have been developed to minimise the development of specific low temperature-related storage disorders. For example, step-wise cooling can be used on cultivars of apple, such as Jonathan, which is susceptible to low temperature breakdown and core flush. This involves four weeks at 2°C, four weeks at 1°C, then storage at 0°C. However, as might be expected, this technique advances ripening and reduces storage and shelf life.

Low temperature disorders can be considered a result of low temperature stress. Plants have developed various biochemical processes for coping with stress that include the expression of specific cold tolerance genes and of heat shock defence proteins. It would seem that developing methods to stimulate natural molecular, biochemical and enzymatic mechanisms of stress-coping may ameliorate susceptibility of produce to low storage temperature stress. For example, short periods of pre-storage exposure to intermediate low temperatures, high temperature stress with hot air or water and a nitrogen atmosphere (i.e. anoxia) have been shown to reduce the susceptibility of different fruit and vegetables to various low temperature injuries, but there has been limited commercial application to date.

If effective management methods are not available, the ultimate method of avoiding physiological disorder is to hold susceptible fruits at a temperature high enough to avoid the disorder being a problem. For commodities susceptible to low temperature-associated physiological disorders, this temperature is usually 3–5°C but is sometimes greater than 5°C. This strategy significantly negates the benefit of using low temperature to minimise metabolic rates, but it is less problematic to market slightly over-mature produce than to have an unsightly disorder present.

Superficial scald

Superficial scald (scald) is a classic storage disorder and has been the most studied physiological disorder in apples over many years. This extensive research has led to its successful management and it is a good example of the multi-faceted approach to managing disorders using breeding, as well as chemical and non-chemical control measures. While a large number of different experimental regimes have been trialled with some success against scald development, several of these treatments are now commercially used to manage the disorder.

Scald is a major physiological disorder that occurs during cold storage of some important apple cultivars, such as Granny Smith. Scald is characterised by brown, irregular patches that appear on the skin during cold storage (Plate 1D). The damage is only superficial, confined to the peel (hence its name) and can be removed with shallow peeling. However, this amount of damage greatly downgrades fruit quality and hence its marketability and grower returns.

Typical of most physiological storage disorders, the development and expression of scald is the result of complex pre- and postharvest interactions. Preharvest factors affecting susceptibility to scald include tree vigour, tree nutrition, field temperatures and rainfall, and fruit size. However, the major factors influencing scald susceptibility are fruit cultivar (the overriding factor), fruit maturity (immature apples tend to be more susceptible) and seasonal conditions (fruit grown in warm, dry areas is more susceptible than fruit grown in cool moist climates). Hence, the simplest solution to the scald problem would be to only grow apple cultivars that do not scald. However, plant breeding is a long-term solution and many of the scald-susceptible cultivars have desirable commercial attributes that warrant development of measures for controlling scald. The severity of scald is also affected by storage conditions such as composition of the storage atmosphere, storage temperature, ventilation of the storage atmosphere and length of time in storage.

It is generally accepted that scald is induced by the oxidation products of the naturally occurring sesquiterpene fruit volatile, α-farnesene. These oxidative products kill the cells in the peel, leading to the classic symptoms in storage. By understanding these causative factors, scald was successfully controlled with chemical antioxidants such as diphenylamine (DPA), but many countries do not now allow the use of DPA and alternative control measures have had to be developed. For example, 1-methylcyclopropene (1-MCP) is now registered in many countries to control scald. It is thought that 1-MCP delays the onset and accumulation of ethylene and consequently α-farnesene production and then its oxidation, which then prevents the expression of the disorder. However, it is important to apply the 1-MCP treatment as soon as possible after harvest. In addition, non-chemical control measures for scald are commercially used, and are suitable for organic production. For example, ultra-low oxygen storage and dynamic controlled atmosphere (DCA) storage (Chapter 7) successfully manage scald in storage.

9
Pathology

Postharvest diseases caused by microorganisms affect a wide range of fruit and vegetables and result in substantial losses. These losses can be severe in tropical areas, where high temperatures and high humidity favour rapid microbial growth, and sound produce can be contaminated by adjacent rotting produce. Furthermore, ethylene produced by rotting produce can cause premature ripening and senescence of other produce in the same storage and transport chamber, rendering them more susceptible to microbial attack. Apart from actual losses due to wastage, further economic loss occurs when the market requirements necessitate sorting and repacking of partially contaminated consignments.

Many bacteria and fungi can cause postharvest spoilage of fruit and vegetables, but the major postharvest diseases are caused by the fungal species *Alternaria, Aspergillus, Botrytis, Fusarium, Geotrichum, Monilinia, Penicillium, Rhizopus* and *Sclerotinia* and the bacteria *Pectobacterium* (formerly *Erwinia*) and *Pseudomonas* (Table 9.1; Plate 2). Most of these organisms are weak pathogens in that they can only invade damaged or senescing produce. A few organisms, such as a few species of *Colletotrichum*, are able to penetrate the skin of healthy produce. Often the relationship between the host fruit or vegetable and the pathogen is reasonably specific. For example, *Penicillium*

Table 9.1 Examples of major postharvest diseases of fresh fruit and vegetables

Crop	Disease	Pathogens
Apple, pear	Grey mould	*Botrytis cinerea*
	Blue mould	*Penicillium expansum*
Banana	Crown rot	*Colletotrichum musae*, *Fusarium roseum*, *Verticillium theobromae*, *Ceratocystis paradoxa*
	Anthracnose	*Colletotrichum musae*
Citrus fruit	Green mould	*Penicillium digitatum*
	Blue mould	*Penicillium italicum*
	Sour rot	*Geotrichum candidum*
Grape, strawberry, leafy vegetables	Grey mould	*Botrytis cinerea*
Papaya, mango	Anthracnose	*Colletotrichum gloeosporiodes*
Peach, cherry	Brown rot	*Monilinia fructicola*
Peach, cherry, strawberry	Rhizopus rot	*Rhizopus stolonifer*
Pineapple	Black rot	*Ceratocystis paradoxa*
Potato, leafy vegetables	Bacterial soft rot	*Pectobacterium carotovora*
	Dry rot	*Fusarium* spp.
Sweet potato	Black rot	*Ceratocystis fimbriata*
Leafy vegetables, carrot	Watery soft rot	*Sclerotinia sclerotiorum*

digitatum rots only citrus fruits while *P. expansum* rots apple and pear fruits but not citrus. Initial breakdown of tissue is often rapidly followed by invasion by a broad spectrum of weak pathogens and saprophytes, which magnify the damage caused by the primary pathogens. The general appearance of many commodities may be marred by surface lesions caused by pathogenic organisms without the internal tissues being affected.

The infection process

Infection of fruit and vegetables by microorganisms can occur either when attached to the plant or during harvesting and subsequent handling and marketing operations. The infection process is greatly aided by mechanical injury to the skin of produce such as weather damage, insect punctures, cut stems, fingernail scratches, abrasions and rough handling. Furthermore, the developmental stage and stress condition of the produce, environmental conditions such as temperature, and natural host defences significantly affect the infection process and the subsequent invasion process. It is important to understand the infection and invasion process in order to implement appropriate treatment strategies to prevent or manage the infection.

Preharvest infection

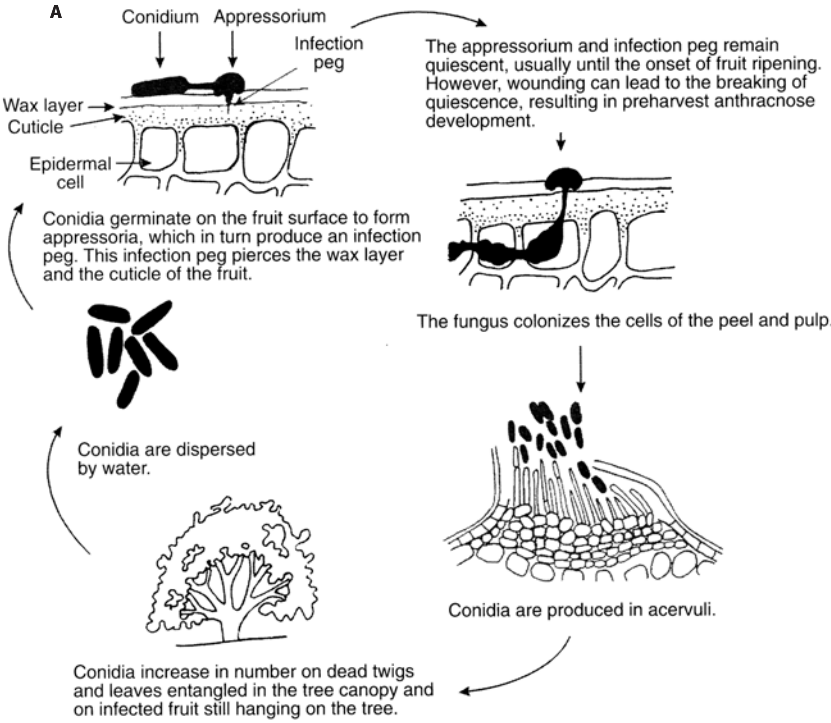
Preharvest infection of fruit and vegetables may occur through direct penetration of the skin, infection through natural openings on the produce, infection spreading from the parent plant and infection through mechanical damage.

Some pathogenic fungi are able to initiate an infection on sound developing fruit, but the infection is often arrested and

Figure 9.1 (right) **(A) Diagram of the characteristic anthracnose disease cycle caused by the plant pathogen *Colletotrichum gloeosporioides* and (B) a transmission electron micrograph of a *C. gloeosporioides* spore germinating on the skin of an avocado fruit (CO = conidium, GT = germ tube, AP = appressorium, IP = infection peg, W = wax layer, and C = cuticle)**

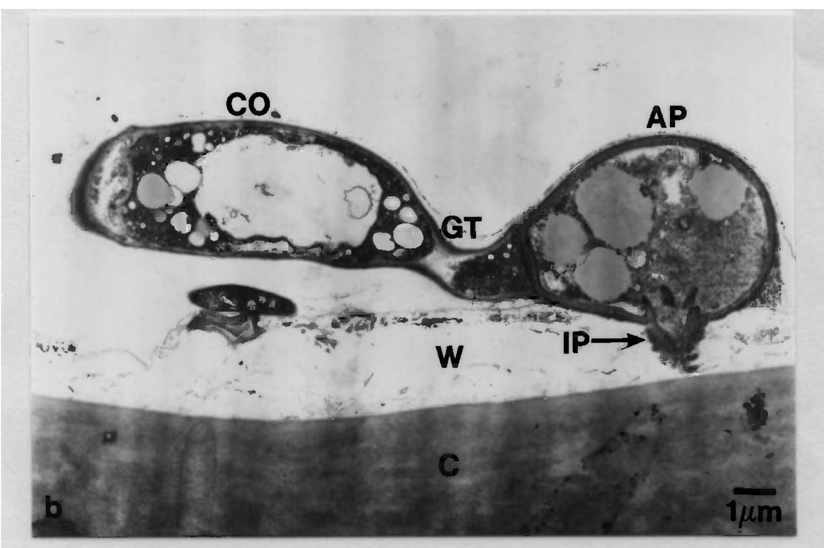
SOURCE Images provided by Tony Cooke and Dr Lindy Coates, Department of Primary Industries and Fisheries, Queensland.

A



Conidium
Appressorium
Infection peg
Wax layer
Cuticle
Epidermal cell
The appressorium and infection peg remain quiescent, usually until the onset of fruit ripening. However, wounding can lead to the breaking of quiescence, resulting in preharvest anthracnose development.
Conidia germinate on the fruit surface to form appressoria, which in turn produce an infection peg. This infection peg pierces the wax layer and the cuticle of the fruit.
The fungus colonizes the cells of the peel and pulp.
Conidia are dispersed by water.
Conidia are produced in acervuli.
Conidia increase in number on dead twigs and leaves entangled in the tree canopy and on infected fruit still hanging on the tree.

B



CO
AP
GT
IP
W
C
b
1µm

remains dormant until after harvest, when the natural resistance of the host decreases and/or conditions become favourable for growth. Organisms that form such latent infections are important postharvest diseases of many tropical and subtropical fruits (e.g. anthracnose disease of mangoes and papayas, crown rot disease of bananas and stem-end rot disease of citrus). An example of this process is the spores of *Colletotrichum* that germinate in moisture on the surface of fruit and within several hours of germination, the tip of the germ tube swells to form a hard-walled structure known as an appressorium. An infection peg from the appressorium may or may not penetrate the skin before the infection is arrested. At some later time, the infection will become active and the host tissue will be extensively invaded by the fungal hyphae. The infection process for *C. gloeosporiodes* is illustrated in Figure 9.1. Infection can also occur via the flower petals in the orchard.

Other pathogenic and/or saprophytic fungi and bacteria can gain access to developing fruit and vegetables through natural openings such as stomates, lenticels, hydrthaodes and growth cracks. Again, these infections may not develop until the host becomes less resistant to the invading organism; for example, when the fruit becomes ripe. An example of this infection mechanism is the penetration of apple lenticels before harvest by spores of *Neofabraea alba* (formerly *Phlyctaena vagabunda*), which manifest in storage as rots around the lenticels. Most sound fruit and vegetables can suppress the growth of pathogenic organisms for a considerable time due to preformed (e.g. cuticle) and induced (e.g. lignification) natural physical barriers (such as in the epidermis and periderm) and chemical defence compounds that are collectively known as phytoalexins (see later in this chapter).

Postharvest infection

As stated above, many postharvest pathogens are unable to penetrate intact skin of produce but readily invade via any mechanical damage in the skin. The damage may be microscopic, but this is often sufficient for the spores and other infectious structures of pathogens present on the produce or in the packinghouse environment to gain access to produce. The cut stem is also a common point of entry for microorganisms. Thus stem-end rot diseases are a significant cause of postharvest wastage of many fruit and vegetables.

Dying and dead floral remnants can also be a ready source of postharvest infection. In the case of grape, *Botrytis cinerea* that infected senescing or necrotic anther tissues can readily invade berries after harvest. Again, as previously discussed, postharvest infection can also occur through direct penetration of the skin by strong pathogens such as *Sclerotinia* and *Colletotrichum*.

Factors affecting development of infection

Probably the most important factor affecting the development of postharvest wastage caused by pathogens is the surrounding environment. High temperature, high humidity and free water favour development of postharvest decay. Chilling injury also predisposes tropical and subtropical produce to postharvest decay, as the damaged cells are open for infection. In contrast, low temperature, low oxygen and high carbon dioxide levels and the correct humidity can restrict the rate of postharvest decay by either retarding the rate of ripening or senescence of produce, or both, and thus depressing growth of pathogens.

Many other factors affect the rate of development of an infection in fruit and vegetables. The host tissue, particularly the pH of the tissue, acts as a selective medium for growth. Fruits generally have a pH below 4.5 and are largely attacked by fungi. Many vegetables have a pH above 4.5 and consequently bacterial rots are more common. Ripening fruits are more susceptible to wastage than immature fruits, so treatments such as low temperature that slow down the rate of ripening will also retard the growth of decay organisms. Underground storage organs, such as potatoes, cassavas, yams and sweet potatoes, are capable of forming layers of specialised cells (wound-periderm) at the site of injury, thus restricting the development of postharvest decay. During the commercial handling of potatoes, periderm formation is promoted with short-term holding at low temperature and high humidity; a process known as curing (see Chapter 11). A type of curing process (possibly by desiccation) has been shown to reduce the wastage of oranges caused by *Penicillium digitatum*. When the fruit is held at high temperature (30°C) and humidity (90% RH) for several days, the orange peel becomes less turgid and lignin is synthesised in the injured flavedo tissue.

Control of postharvest diseases

An integrated approach to disease management, encompassing both preharvest and postharvest activities, needs to be considered for optimum effectiveness.

Preharvest disease control

In most instances, control of postharvest diseases can commence before harvest in the field or orchard. Wherever possible, sources of infection should be eliminated and sprays for the control or eradication of the causal organisms applied. Preharvest sprays are generally not as effective as postharvest application of the chemical directly to the commodity, although some of the systemic fungicides have shown good control of latent infections, such as lenticel rot of apples and brown rot of peaches. However, some care should be exercised in the overuse of preharvest fungicides due to the development of fungicide resistance. An early example of chemical resistance was observed in the rapid development of resistance by *Penicillium* species to the benzimidazole group of fungicides. Preharvest sprays of such fungicides are not recommended if the same fungicide is being relied upon for postharvest control of the target organism.

Care during harvest and subsequent handling can minimise mechanical damage and reduce the possibility of infection and subsequent wastage. The weather at harvest should be dry and cool to avoid further contamination and infection. It is unwise to harvest some fruits such as citrus after rain or heavy dew as the peel is turgid and easily damaged.

Postharvest disease control

Postharvest disease control methods can be classified under three broad categories: chemical, physical and biological treatments. The effectiveness of any treatment depends on three main factors: (1) the ability of the treatment to reach the actual site of the pathogen, (2) the level and sensitivity of the infection, and (3) the sensitivity of the host produce to infection.

The time of infection and the extent of development of the infection are critical to whether a fungus can be controlled.

For example, *Penicillium* and *Rhizopus* invade wounds during harvest and subsequent handling operations and are relatively easily controlled by fungicide application to the surface of the commodity. In contrast, *Botrytis* infects strawberry fruit in the field some weeks before harvest or even at the time of flowering and is therefore more difficult to control.

The requirements of a control measure depend on the marketing strategy for the commodity and the type of infection. For citrus fruit, which have a relatively long postharvest life, the treatment needs to prevent primary infection and also sporulation so that nearby fruits are not contaminated. Strawberries have a short postharvest life and treatment is aimed at preventing the spread of the field-induced infection of *Botrytis*. In other words, the treatment has to match the subsequent marketing of the commodity. It is neither necessary nor desirable to treat a short-life commodity with a fungicide that has a long residual activity.

Chemical treatments

Chemical control of postharvest diseases has become an integral part of the handling and successful marketing of fruit over the past 50 years. The success of chemical treatments depends on many factors, including: the initial spore load, the depth of the infection within the host tissues, the growth rate of the infection, temperature and humidity, and the depth to which the chemical can penetrate the host tissues. Moreover, the applied chemical must not be phytotoxic (i.e. must not injure the host tissues) and must be permitted for use by the food and health regulations. Over the years, a wide range of chemicals has been used for the control of postharvest losses. Initially, only naturally available chemicals were available, with alkaline inorganic salts such as sodium tetraborate (borax) and sodium carbonate (washing soda) and sulphur compounds utilised to provide some protection. With developments in biochemical synthesis and manufacturing capability, the ability to design, test and synthesise new compounds has resulted in the widespread use of synthetic fungicides. The early fungicides were contact chemicals and thus needed to be applied carefully to ensure complete coverage of the produce.

A major advance was development of the benzimidazoles such as thiabendazole (TBZ) and benomyl in the 1970s, which rapidly superseded earlier chemical treatments due to having a wide spectrum of antifungal activity at extremely low concentrations. These compounds were also systemic and therefore provided substantial residual activity. The imidazoles were introduced in the late 1970s and imazalil and prochloraz still remain in wide postharvest usage. More recently, the emergence of new specific chemical types and the need to better manage fungicides have led to the development of the concept of 'reduced risk', which is a special classification developed and approved by the USA Environmental Protection Agency. This classification is for specific uses of pesticides that have low risk to human health, low toxicity to non-target organisms, low potential to contaminate water or other environmental resources, and/or that broaden the adoption and effectiveness of integrated pest management strategies.

Despite being called fungicides, most of these chemicals are generally fungistatic in action rather than fungicidal. Fungistats inhibit spore germination or reduce the rate of germination and growth after germination rather than cause death of the organism (fungicides), and they must come into direct contact with the organism to be effective. A few chemicals, such as chlorine and sulphur dioxide, are true fungicides. Chlorine is commonly added to wash-water to kill bacteria and fungi, while sulphur dioxide is lethal to *Botrytis* on grapes.

The continuing evolution of postharvest chemical control can be illustrated with citrus fruits. Green (*Penicillium digitatum*) and blue (*P. italicum*) moulds are the major postharvest diseases of citrus, with green mould being more prevalent in humid areas. Stem-end rots are also significant causes of postharvest losses in more humid climates. Borax and sodium carbonate were used to give some control but were superseded by sodium orthophenol phenate (SOPP) in the 1960s. The introduction of thiabendazole and benomyl in the 1970s rapidly superseded earlier chemical treatments, although they are inactive against *Rhizopus, Alternaria, Geotrichum* and soft rot bacteria. SOPP can give some control of soft rots, which has allowed it to remain in limited use. However, the use of benzimidazoles soon led to the development of resistant strains of *Penicillium* and forced the search for alternative treatments. This led to the introduction in the 1980s of the imidazole-type fungicides, imazalil and prochloraz, which are also very effective against a wide range of fungi including some that are resistant to the benzimidazoles. But fungicide resistance to imazalil has quickly developed despite it being genetically more difficult for *Penicillium* to develop resistance to this fungicide. This illustrates the need to properly use postharvest fungicides and continually manage their use with strict plans to avoid fungicide resistance. The continued development of new fungicides continues, where several fungicides of newer chemical types such as pyrimethanil and a combination of fludioxonil and azoxystrobin, are now available to control citrus decay.

The development of new fungicides is expensive and time consuming, and all new fungicides must navigate stringent approval mechanisms for use by regulatory authorities in individual countries. This process is to ensure that new chemicals are not toxic at the concentrations used and are not deleterious to the health of workers and the environment. Regulatory authorities also set maximum residue limits (MRLs) for approved fungicides and empower government inspection services to monitor the use of products to ensure they are only being used for the specific approved purpose.

Despite these stringent approval and usage protocols, there are growing consumer concerns about the use of synthetic chemicals, which has translated into considerable pressure now on the horticultural and agricultural industries to use non-synthetic chemical methods of disease control. Desirable alternative treatments are perceived to be plant metabolites, physical treatments or biological controls, as they are seen as more natural and avoid the chemical residue problems associated with synthetic chemical use.

Plant metabolites

The control of microbial growth using endogenous plant metabolites, while still being a chemical treatment, is perceived by many consumers as more acceptable. Many of these compounds are classified as generally recognised as safe (GRAS) chemicals and/or are approved food additives.

The organic volatile compounds produced by fruit and vegetables are being examined for their antimicrobial activity, as many of the flavour volatiles – especially aldehydes (such as acetaldehyde and hexanal) and alcohols (such as ethanol) – have been shown to inhibit the development of decay on a range of produce. Their volatility is an advantage as it allows their ready use as vapours released into the atmosphere, which can move around produce to their site of action. However, there are still a number of issues that need to be resolved before commercialisation can occur. Not the least of these is that most volatile compounds need to be applied at concentrations much greater than levels occurring naturally in produce. Most probably, commercial usage would favour chemically synthesised compounds rather than extracts from plant material. This raises the question of when a compound ceases to be natural and becomes an applied chemical in the minds of regulators and consumers.

In a similar vein, the volatile essential oils from plants, which are mainly mono- and sesquiterpenes, have long been known to have antimicrobial properties, which has led to their long-standing use in human therapy. Many essential oils from registered food grade materials or those classed as GRAS have the potential for use as alternative antifungal and antibacterial treatments for fresh produce. Essential oils of interest include those obtained from a range of citrus fruits, culinary herbs and spices such as thyme, cinnamon and lemon myrtle, lemongrass and tea tree (*Melaleuca* spp.).

Phytoalexins

Phytoalexins are plant metabolites produced by a fruit or vegetable that provides resistance against invading pathogens. In many instances, the greater susceptibility of produce to rotting during ripening and senescence has been attributed at least in part to a decline in their levels of phytoalexins. Phytoalexins are chemically diverse, with different types being characteristic of particular plant species. Many are phenolic derivatives and include terpenoids, glycosteriods and alkaloids. Examples of phytoalexins include resveratrol (3,5,4'-trihydroxy-*trans*-stilbene), which is naturally produced by grapes and various berry fruits, and coumarins such as scoparone (6,7-dimethoxycoumarin) and scopoletin (7-hydroxy 6-methoxycoumarin), which are produced by citrus fruits.

Activation of a defence system depends on signals from the infected area that can mobilise a short-term response to deploy reactive oxygen species such as superoxide and hydrogen peroxide to kill invading cells. A longer term defence response involves signalling from the infected site to sound tissue by endogenous plant hormones. Reception of the signal leads to global changes in the genes and enzymes involved in the production of phytoalexins.

Stimulation of phytoalexin activity in postharvest produce can lead to inhibition of fungal growth and can be considered a preferred strategy for natural disease management. Such stimulation can be by physical, biological or chemical elicitors. Chemical elicitors can be applied pre- or postharvest, with most interest in natural signalling compounds such as gibberellic acid, methyl jasmonate and salicylic acid, and hence the aim is to simulate the natural process. Elicitors can also be inorganic salts such as potassium phosphonate that induce resistance in orange fruit to *P. digitatum* through induction of scoparone.

As might be expected, synthetic compounds have been developed that act as elicitors. An example is acibenzolar, which is currently marketed a potent elicitor of coumarin phytoalexins. It has activity against a wide range of fungi such as *Alternaria* sp., *Fusarium* sp., *Rhizopus* sp. and *Botrytis cinerea*. Of course, the use of such elicitors would not qualify as a natural treatment even though they are stimulating a natural process.

Physically induced resistance can be achieved with heat treatment, ionising irradiation and UV-C irradiation, while biologically induced resistance can come from a number of antagonistic microorganisms that are capable of inducing defence reactions and biological extracts such as yeast cell wall extracts. These technologies are discussed in the following sections.

Physical treatments

Physical treatments include handling procedures that minimise postharvest injury and hence inhibit the entry of microorganisms to the commodity. Careful handling should be implemented in every postharvest system to minimise damage. Such procedures involve low cost and low technology. Associated with careful handling is a good sanitation program in the postharvest environment that minimises the background level of spores and hence reduces their contact with produce. An important benefit of packaging is the protection it gives to produce to resist damage during handling and transport and to limit cross contamination.

The use of low temperature during handling and storage is the next most effective physical method of postharvest wastage control. While the susceptibility of most tropical and subtropical produce to chilling injury limits the benefits to be gained from low temperatures, holding such produce at say 15°C is more beneficial than holding at ambient temperatures which can be greater than 30°C.

Heat treatments such as moist hot air, hot water dips and hot water brushing have commercial application for control of postharvest wastage in a range of fruits. Advantages of heat treatments are that they can control surface infections as well as infections that have penetrated the skin, and they leave no chemical residue. The beneficial effect of heat is at least partly due to enhanced formation of lignin and related compounds, which prevent invasion by germinating fungal spores. The absence of chemical residues makes it necessary to ensure strict hygiene is practised to prevent re-contamination of the produce by microorganisms. This may also be achieved with the application of a fungicide, although at lower levels than those required without a hot water dip. Hot water dips must be precisely controlled as the range of temperature (commonly 50–55°C) necessary to control wastage approaches temperatures that damage produce quality.

Ultraviolet radiation can be used against postharvest pathogens directly by treatment of water used in packinghouses. Irradiation of fruits, particularly of citrus, with UV light at 254 nm has been found effective in inhibiting mould growth. The use of UV light is further enhanced by subsequent exposure to a hot water dip. The mode of action appears to be by stimulating the fruit to increase the production of lignin in the surface layers and of endogenous phytoalexins as discussed in the previous section.

Other important factors to minimise microbial growth, such as the use of elevated carbon dioxide, reduced oxygen and reduced ethylene levels, and better control over humidity conditions around produce have been mentioned earlier. Ionising radiation can also inhibit microbial growth at higher irradiation levels, but such levels can adversely affect produce quality (see Chapter 11).

Biological treatments

There are potentially many biological control agents to control postharvest diseases. These include fungi, yeasts and bacterias

(Table 9.2). However, despite considerable research efforts, relatively few biological control agents have progressed to commercial application. For biological control to be effective in the postharvest environment, the storage conditions must allow the biological agent to remain viable and an efficient application method is required to fully cover produce surfaces. Needless to say, the cost of the treatment needs to generate a greater economic return.

Table 9.2 Biological agents with inhibitory activity on postharvest disease organisms

Commodity	Disease	Biological agent
Apple	Blue mould Grey mould	*Pseudomonas syringae, Pseudomonas cepacia, Cryptococcus* spp. *Pseudomonas cepacia, Cryptococcus laurentii, Acremonium breve, Candida oleophila*
Pear	Blue mould/grey mould Grey mould Mucor rot	*Pseudomonas cepacia* *Pseudomonas gladioli* *Cryptococcus laurentii, Cryptoccocus flavus*
Stone fruit	Brown rot	*Bacillus subtilis*
Citrus	Sour rot Green mould, blue mould	*Bacillus subtilis, Trichoderma* spp. *Candida oleophila*
Grape	Grey mould	*Trichoderma harzianum, Pichia guilliermondi*
Strawberry	Grey mould	*Trichoderma harzianum*
Pineapple	Penicillium rot	Attenuated strains of *Penicillium* spp.
Potato	Soft rot	*Pseudomonas putida*
Tomato	Grey mould, Alternaria rot	*Pichia guilliermondi*

Biological control agents can suppress pathogens by a range of mechanisms. Direct attack, competition for space and nutrients and elicitation of heightened host defence mechanisms are generally considered to be the mechanisms of action. Control of postharvest diseases can also occur through the biological agent producing chemicals that are toxic to the disease organism (e.g. the synthesis of natural antibiotics). This mechanism is generally not considered desirable for food crops because of antibiotic allergies in a proportion of the population.

A widely studied example of biological control is the use of the bacterium *Bacillus subtilis,* which has been shown to control a range of fungal species, including brown rot of peaches and citrus green mould, sour rot and *Alternaria* centre rot. In these cases, the controlling agents were thought to be antifungal substances produced by the bacterium which prevent mould development. There is a range of commercial biocontrol agents based on *B. subtilis* that are marketed for pre- and postharvest diseases of a range of fruit.

Antagonism between organisms is a highly promising area of biological control, where the growth of a non-pathogenic organism prevents the growth of a pathogenic organism. The antagonistic microorganism may be added from an external source, or indigenous microflora on the surface of the host can be stimulated in a way that the incoming pathogen cannot develop on the plant surface.

It is a lengthy process to discover a potential biological control agent for use on a commodity, prove its safety and effectiveness on the target crop, and confirm its ability to survive in the new environment but not become a problem by having undesirable side effects. Some biological control methods may have additional problems, such as inducing allergic responses in humans, and need to be rigorously tested for human toxicity and carcinogenicity in the same manner as potential new fungicides are screened, even though many antifungal substances or the organisms themselves may occur naturally. Nonetheless, with the likely eventual loss of effectiveness of chemical treatments due to development of resistance and consumer aversion to synthetic chemicals applied to foods, recent years have witnessed increasing interest in biological control methods for postharvest diseases.

10
Quality evaluation and management

Quality as defined by all industries identifies the desired attributes of products being marketed. These attributes are intended to match the expectations of a purchaser who may be expected to pay a premium price and/or provide repeat purchases of the product if the quality criteria are consistently maintained. Fruit and vegetable producers, unlike industrial manufacturers, have only limited control over the attributes of harvested produce due to the variable growing environment and natural biological variation. However, produce are marketed to consumers who expect consistency of a quality that meets their personal preference. These quality expectations are based on a range of learned criteria based on past experiences. The purchase habits of consumers are typically conservative and require consistency of quality with repeat purchases. There is, however, a growing segment of the community that is receptive to new produce or innovations to existing produce that add to the eating experience – the kiwifruit industry is an example of such innovation, with development of fruit with different flesh colour and skin texture that expand the overall market for kiwifruit. While good experiences with a purchase reinforce the willingness for repeat purchase, a bad experience such as the purchase of over-stored fruit can have longer term detrimental effects for usage of that commodity.

While desirable quality parameters of fruit and vegetables generally relate to intrinsic characteristics or compositional factors of the particular commodity, they are also overlaid with a range of government imposed regulatory criteria; for example, pesticide residue limits that may or may not relate to eating quality. The successful quality management of fruit and vegetables then needs to encompass a diverse range of considerations and requirements.

Quality criteria

Quality criteria can be divided into external and internal factors. In terms of marketing, external criteria might be considered of paramount importance, as this is the initial contact between buyer and the product. Accordingly, measures are often taken to try to ‘improve’ external quality. Examples of such measures include waxing of apples, degreening of oranges, and orange-coloured mesh bags to reinforce colouration of oranges. However, if consumers are disappointed by poor internal quality, an eventual negative response will be a reduction in the number of repeat purchases. For instance, consumers are often disappointed by poor organoleptic properties of early season fruit (e.g. immature nectarines which fail to ripen properly) or out of season fruit (e.g. mealy apples that have been over-stored). Some important quality criteria for consumers are: appearance, including size, colour, shape; surface and internal defects; mouthfeel or texture; flavour; and nutritional value.

Appearance

People 'buy with their eyes' and learn from experience to associate desirable qualities with a certain external appearance. A rapid, visual assessment can be made on the basis of size, shape, colour, condition (such as freshness), and/or the presence of surface defects or blemishes.

Size can be easily measured by circumference, diameter, length, width, weight or volume. Many fruits are graded according to size, often by diameter measurement or weight, with similar sizes being packed together to give a uniform pack, which facilitates marketing and retail sales. For example, certain size standards are set for mangoes and other fruits based on fruit diameter or associated count number per package. However, with supermarkets now obtaining supplies directly from producers, packaging by unit weight is increasingly common.

Shape is a criterion that often distinguishes particular cultivars of fruit. Characteristic shapes are usually demanded by consumers, who will often reject a commodity which lacks the characteristic shape. For example, attempts to market a straight banana were unsuccessful, apparently because this shape was considered abnormal. The amount of bend in banana is stipulated in the EU market, so the consumer there never knows that a banana can be straighter. Misshapen fruit and vegetables are poorly accepted and usually bring a lower price. Shape is often a problem in breeding programs. Although a superior eating or storing product may be obtained by breeding, if its shape is unusual it will be less readily marketed with extensive re-education of consumers required.

One of the distinguishing features of fruit and vegetables is that they are the only major group of natural foods with a variety of bright colours. These are often used in the marketplace merely to brighten up the presentation of foods. Parsley contains relatively high levels of numerous micronutrients compared to fruit and other vegetables, yet is used almost exclusively in Western society to add colour and flavour to meat and fish dishes. Colour changes in ripening fruit have been correlated by consumers with the conversion of starch to sugar (i.e. sweetening) and the development of other desirable attributes, so that the correct skin colour is often the sole criterion used to purchase a commodity. Standardised colour charts are now available for the visual assessment of ripeness in many fruit; for example, tomatoes, pears, apples and bananas (Plates 3 and 9). However, such subjective assessments may be misleading. For example, bananas ripened at higher than optimum temperatures do not show full loss of green colour even though the flesh is adequately ripened.

Defects

Normal appearance is extremely important in the marketplace. It is often the only criterion available to the buyer of the commodity since on-the-spot taste-testing is rarely encouraged at retail outlets, although it is often practised at wholesale markets. Consumers have firm ideas on what constitutes normal appearance, and any deviation will be considered a defect. Wilting of leafy vegetables is obviously a defect and therefore unacceptable to consumers. Skin blemishes, such as bruises, scratch marks and cuts, detract from appearance and on most markets detract from price, even when the blemishes reduce neither keeping quality nor eating quality. Nonetheless, although a premium price may be obtained for produce that is free from blemishes there may still be a market for lower grade produce. Consumers in less affluent markets tend to be more accepting of physical defects through economic necessity. This may result in a greater proportion of a crop that reaches the market being sold and consumed but with a reduced return to traders.

Mouthfeel

Mouthfeel, including texture, is the overall assessment of the feeling the food gives in the mouth. It is a combination of sensations derived from the lips, tongue, walls of the mouth, teeth and even the ears. Each of these areas is sensitive to small pressure differences and responds to different attributes of the produce. Lips sense the type of surface being presented; for instance, they can distinguish between hairy (pubescent) and smooth (glaborous) surfaces. Teeth are involved in determining rigidity of structure. They are sensitive to the amount of pressure required to cleave the food and to the manner in which the food gives way under the applied force. The tongue and walls of the mouth are sensitive to the types of particles generated following cleavage by the teeth. The extent of expressed juice is also assessed. Ears sense the sounds of the food being chewed, and intimately complement mouthfeel. Sound is vitally important in produce such as celery, apples and lettuce, where crispness is a critical attribute. The combined effect of these responses creates an overall impression of the mouthfeel of the produce.

Flavour

Flavour is comprised of taste and aroma. Taste is due to sensations felt on the tongue. The four main taste sensations are

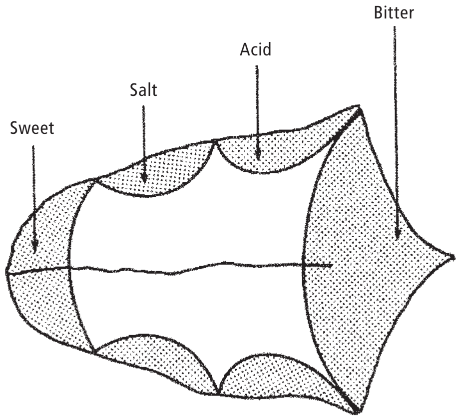


Figure 10.1 Areas of taste sensation on the tongue

sweet, salt, acid (sour) and bitter, with each sensation perceived on a specific area of the tongue (Figure 10.1). All food tastes elicit a response on one or more of these areas. The taste of fruit and vegetables is usually a blend or balance of sweet and sour, often with overtones of bitterness due to tannins. Fruit and vegetables are not naturally salty (although the taste of umami is found in some mushrooms, such as shitake). Aroma is due to stimulation of the olfactory senses in the nose by volatile organic compounds, some of which have been outlined in Chapter 2. Pain is now a recognised sensory quality which may be exemplified by 'hot' chillies, which damage the linings on the tongue and in the mouth generally.

Nutritional value

Encouragement by public health bodies to increase consumption of fruit and vegetables to benefit from the wide range of vitamins, minerals, dietary fibre and more recently antioxidants has been discussed in Chapter 2. However, nutritional value is probably the least important consideration in determining a consumer purchase, since most nutrients can neither be seen nor tasted. For example, fruit and vegetables are the sole source of vitamin C in the diet of many people, yet only a minority buy a particular type of fruit or vegetable because it contains more vitamin C than another type. Even so, nutritional properties of crops such as avocados have been successfully promoted as being 'cholesterol free', while oranges are widely perceived as being high in vitamin C even though the level ranks as only moderate compared to other types of produce.

Promoting increased consumer awareness of the health benefits that can be derived from consumption should be an aim of the fruit and vegetable industry. Apart from enhanced health of the community, it will also lead to increased sales. A joint Australia and New Zealand industry-focused research and development project called 'Vital Vegetables' is an example of putting such aspirations into practice. The project identified crops with high nutritional value, optimised methods of production and worked with grower groups to commercially market the vegetables based on their health benefits.

Postharvest factors influencing quality

Not all changes in harvested produce equate to loss of quality. The obvious example is climacteric fruits such as bananas and tomatoes that are picked at the mature-green stage of development and allowed to ripen off the plant to optimum eating quality. Nonetheless, the principal concern with non-climacteric produce is preventing loss of the existing quality. This deterioration in quality can be caused by a variety of stresses, which may be grouped into four general but often inter-related categories: metabolic stress, transpiration (water) stress, mechanical injury stress, and microbial damage. These issues have been discussed in earlier chapters but in summary, metabolic stress through either normal or abnormal metabolism leads to senescence or the development of physiological disorders, respectively; while transpiration results in loss in physical and nutritional quality as well as direct loss in saleable weight. Mechanical injury causes loss of visual quality through unsightly abrasions, bruises, cuts and tears but can also lead to an increase in the general metabolic rate (wound response) as the produce tries to seal off the damaged tissues and transpiration increases because natural barriers against the loss of water have been damaged. Microbial wastage, although severe, often arises as a secondary stress since proliferation is generally facilitated by mechanical injury, transpiration and/or metabolic changes – such as senescence and physiological disorders.

Some of the major handling factors which contribute to loss of quality of harvested produce are discussed below.

Harvesting

Mechanical damage during harvesting and associated handling operations can result in defects on the produce and permit invasion by disease-causing microorganisms. The inclusion of dirt from the field can aggravate this situation. Produce can overheat and rapidly deteriorate during temporary field storage. Failure to sort and discard immature, overripe, undersized, misshapen, blemished or otherwise damaged produce creates problems in the subsequent handling and marketing operations.

Transport and handling

Rough handling and transport over bumpy roads damages produce by mechanical action. At high temperatures, produce will overheat, especially if there is inadequate shading, ventilation and/or cooling. Transport on open trucks can result in sun-scorch of the exposed produce. Severe water loss, especially from leafy vegetables, can also occur under these conditions. Inappropriate packaging (e.g. overfilling, underfilling) may result in physical damage of produce due to bruising or to abrasion as the commodity moves about during transport. Temperature variations can lead to condensation, which may encourage decay and weaken packages.

Storage

Delay after harvest in placing produce into the appropriate storage conditions often facilitates rapid deterioration in quality. Poor control of storage conditions, over-long storage and inappropriate storage conditions for a particular commodity will also result in a poor quality product. With mixed storage of different commodities, ethylene produced by one produce (e.g. ripening fruit) can promote rapid senescence of another produce (e.g. leafy vegetables). Storage at temperatures that are too low may induce physiological disorders or chilling injury. High temperature and high humidity can encourage both superficial and internal mould growth and stimulate activity of infesting insects. However, where only short-term storage is required, the cost-effectiveness of low temperatures should be evaluated – can a higher temperature with its lower energy usage give the desired storage life?

Marketing

A substantial reduction in quality can occur in produce displayed for lengthy periods in retail outlets because of poor organisation. Major causes of quality reduction during marketing include water loss leading to wilting, browning of rambutans, undesirable ripening (e.g. softening of apples) and senescence (e.g. yellowing of leafy vegetables) under poor temperature and humidity conditions, mechanical damage associated with rough handling by staff and customers, and associated disease development. Refrigerated sections were introduced into many retail outlets to minimise deterioration of display items, but refrigeration can bring its own problems if, for example, chilling-sensitive produce are placed at low temperature. A simpler solution to reduce quality losses can be through improved organisation so that produce spend minimal time on display. An interesting marketing problem is postharvest greening of potatoes that is caused by the practice of displaying cleaned potatoes in relatively bright light in supermarkets. While greening is merely the synthesis of chlorophyll, it is strongly associated with accumulation of the toxic glycoalkaloid, solanine.

Treatment residues

Residues of pesticides and other chemicals is an increasingly important factor impinging on postharvest quality. Insecticides and herbicides are often applied preharvest, fungicides may be used both preharvest and/or postharvest, while fumigants may be used for insect disinfestation or disease control. All applied chemicals can leave residues in the commodity which, although not detectable by the consumer, must be considered in relation to the health risks to the community and is certainly considered undesirable by the consumer.

Determination of maturity

Maturity is an integral component of quality, especially in the context of commercial maturity. There is a clear distinction between 'physiological' and 'commercial' or 'horticultural' maturity. The former is a particular stage in the development of a plant or plant organ while the latter is concerned with the time of harvest as related to a particular end-use that can be translated into market requirements. At optimum commercial maturity, produce should be at optimum consumer quality.

Physiological maturity refers to the point in the development of a plant or plant part when maximum growth has been achieved and the plant or plant part has matured to the extent that the next development stage can be completed. In the case of fruits, ripening can be considered the next development stage, preceding the senescence stage. Clear distinctions between the stages of development – namely, growth, maturation, ripening and senescence – in the development of a plant organ or organism are generally not easy to define (see Chapter 3). This is because transitions between the various development stages are often slow and/or indistinct. Nevertheless, in fruits in particular, measurement of physiological (e.g. respiration and ethylene production) and/or biochemical characteristics (e.g. sugar/acid ratios) can give reliable estimates of the degree of maturity for specific commodities.

Commercial maturity is the characteristic state of a plant organ required by a market. Commercial maturity often bears little relation to physiological maturity, and may occur at any

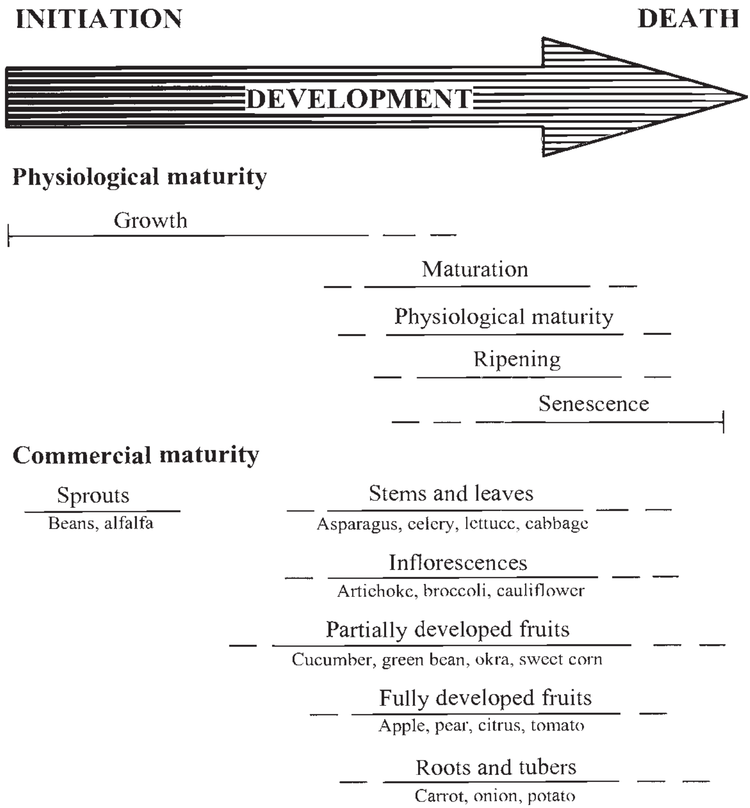


Figure 10.2 **Commercial maturity in relation to developmental stages of the plant**

SOURCE Adapted from A.E. Watada, R.C. Herner, A.A. Kader, R.J. Romani and G.L. Staby (1984) 'Terminology for the description of developmental stages of commercial crops', *HortScience* 19: 20–21.

stage during development, maturation, ripening or senescence. Examples of commercial maturity include bean sprouts (during development), cucumbers (during maturation) and strawberries (during ripening/senescence). The terms immaturity, optimum maturity and over-maturity can be related to these market requirements. Thus, there must be an understanding of each in physiological terms, particularly where storage life and quality when ripe are concerned. Some examples of commercial maturity in relation to physiological age are shown in Figure 10.2.

Ripening, as applied to fruit, is the process by which a fruit attains its maximum desired eating quality. Before the ripe stage, a fruit is said to be under-ripe, and after it is overripe. The three ripeness conditions cannot be clearly defined physiologically because they are subjective judgments and thus will vary among consumers. The under-ripe condition overlaps the mature stage of development, while the overripe condition overlaps the senescence stage of development. Consider the pear, which some relish at a very soft succulent stage while others prefer it at a crunchier texture stage. The potential ripe quality is determined by many factors of which the stage at which the fruit was harvested is vitally important.

Determination of commercial maturity

Commercial maturity indices generally involve some expression of the stage of development (growth, maturation or ripening) and usually require determination of some characteristic known to change as the plant material develops. They may involve taking decisions about levels of market and consumer acceptability, and generally necessitate making objective measurements, subjective judgments or both. Objective and subjective assessments may be destructive or non-destructive in nature.

Many criteria for judging maturity are based on a variety of characteristics including: time from flowering or planting (calendar date), accumulated heat units, size and shape, skin or flesh colour, light transmittance or reflectance, flesh firmness, electrical conductance or resistance, chemical composition (e.g. starch, sugar, acid), respiratory behaviour and ethylene production, and time to ripen. Some examples of when to harvest are given in Table 10.1. To be practical, maturity tests should ideally be simple and rapid and readily applied in the field. They are ideally non-destructive. A description of some methods follows.

Table 10.1 **Established methods for evaluation of commercial maturity of selected horticultural produce**

Maturity index	Produce
Abscission	Rockmelon
Accumulated heat units	Pea
Astringency	Persimmon
Colour	Tomato
Dry matter content	Mango, kiwifruit
Firmness	Pea
Internal ethylene	Apple
Leaf wilting	Onion
Oil content	Avocado
Shape	Banana
Size	Gherkin
Soluble solids/acid ratio	Orange, grape
Sound on thumping	Watermelon
Starch-iodine staining	Apple

Calendar date

For perennial fruit crops grown in distinctly seasonal climates which are relatively uniform from year to year, the calendar date for harvest can be a useful guide to commercial maturity. This approach relies on a reproducible date for the time of flowering and a relatively constant growth period from flowering through to maturity. Time of flowering is largely dependent on temperature, and the variation in the number of days from flowering to harvest can be calculated for some commodities by use of the degree-day concept (see below). Calendar-based harvest dates are usually derived from growers' experience with crops in a specific environment.

Heat units

The time required for the development of the fruit to maturity after flowering can be made by measuring the cumulative 'degree days' or 'heat units' in a particular environment. It has been found that a characteristic number of heat units or degree days is required to mature a crop. Under unusually warm conditions maturity will be advanced and under cooler conditions delayed. The number of degree days required for a crop to reach maturity is determined over several years from the sum of the differences between the daily mean temperatures and a fixed base temperature (commonly the minimum temperature at which growth occurs) over the whole growing period. The total number of degree days over the growing season (e.g. 1000 degree days) is then used to forecast the probable date of maturity for the current year. This heat unit approach is extremely helpful in planning planting, harvesting and factory management programs for annual processing crops such as corn, peas and tomatoes.

Shape and size

Fruit shape may be used in some instances to decide maturity. For example, the fullness of the 'cheeks' adjacent to the pedicel may be used as a guide to maturity of mangoes and some stone fruits. Size is generally of limited value as a maturity index in fruits but is widely used for many vegetables – especially those marketed early in their development, such as zucchinis. With such produce, size is often specified as a quality standard. Large size generally indicates commercial over-maturity and undersized produce indicates an immature condition.

Shape and size give rise to the volume parameter which, when expressed as a function of weight (mass), gives density (e.g. g/mL). This ratio is a useful determinant of maturity in some produce (e.g. potatoes) and to grade frost damaged citrus fruits. It can also be used to sort defects (e.g. disorders which result in internal cavities). Commercial sorting machines use load cells to weigh fruit, and cameras with multiple views of fruit (mirrors or rolling fruit) to estimate volume, and thus can calculate density.

Colour

The loss of green colour, often referred to as the 'ground colour' (i.e. the background colour), of many fruits is a valuable guide to maturity. There is initially a gradual loss of intensity of colour from deep green to lighter green, and with many commodities complete loss of green with the development of yellow, red or purple pigments (e.g. tomatoes) (Plate 3). Ground colour, as judged against prepared colour charts, is a useful index of maturity for apples, pears, stone fruits and mangoes but is not entirely reliable as it is influenced by factors other than maturity (e.g. nitrogen nutrition during growth).

For some fruits, additional colour superimposed on the ground colour can be a useful indicator of maturity. Examples are the red or red-streaked apple cultivars and the red blush

Figure 10.3 High-speed colour and defect sorting of cherries

on some cultivars of peach. Such colour development is usually dependent on exposure to sunlight. For certain tropical fruits, skin colour is a reliable guide to commercial maturity. For example, the appearance of a trace of yellow at the apical (distal) end of papaya fruit is sometimes used to determine the time of harvest. Nonetheless, such fruit would benefit from a longer period on the tree, until about one-third of the fruit is yellow. After this time, papaya fruit ripening is quicker and eating quality is better but the shelf life will be shorter.

Objective measurement of colour is possible using a variety of light reflectance or transmittance spectrophotometers. Colour analysers can also be used to sort horticultural produce on the basis of both colour and dimensions (Figure 10.3). Electronic colour vision sorting is now common for many crops (e.g. apples, citrus and tomatoes). Because the capital cost of sophisticated equipment is high, its use is largely restricted to packinghouses with a high throughput of produce. A commercial field instrument that non-destructively measures the difference in absorbance between 670 and 720 mm (I_{AD} index) is used to assess peel chlorophyll content in many fruits.

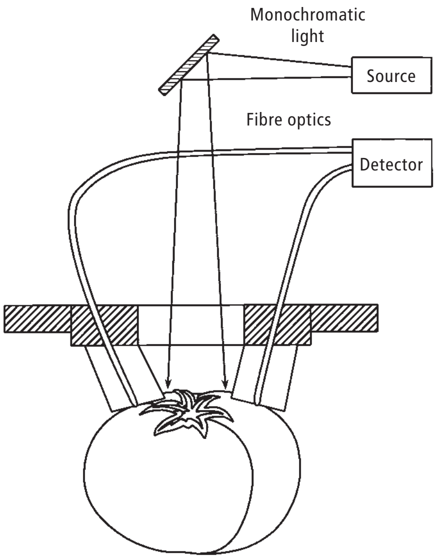


Figure 10.4 **Diagram of the geometry used to make transmission measurements of fruit.** The incident light that enters the produce directly under the source is scattered and absorbed by the produce. Some of the scattered light transmitted by the produce is collected by the shielded detectors placed directly on the surface of the produce. Transmission spectra are generated by varying the wavelength of the incident light.

SOURCE Adapted from G.S. Birth, G.G. Dull, J.B. Magee, H.T. Chan and G.G. Cavaletto (1984) 'An optical method for estimating papaya maturity', *Journal of the American Society for Horticultural Science* 109: 62–69.

Figure 10.5 **NIR sorting of oranges**

Changes in internal colour and other physicochemical characteristics can be gauged by measurement of the transmittance/absorbance of light through the sample (Figure 10.4). Such measurements can be made rapidly, at the speed of modern fruit conveyors. For example, internal green colour, a defect of gold kiwifruit, and internal browning of apples can be readily assessed. Grading of fruit for internal chemical properties, such as sugar level, can be achieved using near infrared spectroscopy (Figure 10.5). This is discussed in more detail in Chapter 11.

Flesh firmness

As fruits mature and ripen they soften, largely by dissolution of pectic substances in the middle lamella of cell walls. This softening can be estimated subjectively by finger or thumb pressure.

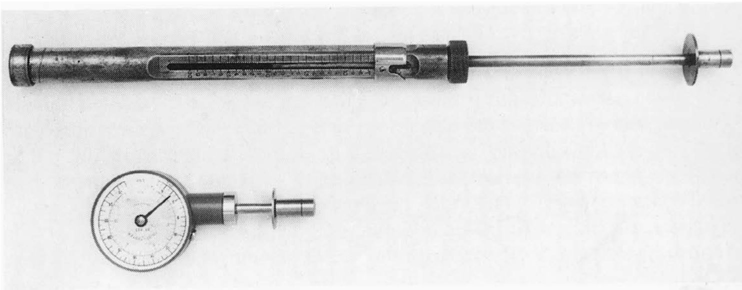


Figure 10.6 **Magness-Taylor (top) and Effegi (bottom) fruit pressure testers**

However, more objective measurement, yielding a numerical expression of flesh firmness, is possible with a fruit pressure tester (penetrometer). These testers measure the pressure at which flesh yields to the penetration of a standard diameter plunger inserted to a standard depth. Commonly used penetrometers are the Magness-Taylor and UC Fruit Firmness testers, and the smaller and more convenient Effegi penetrometer (Figure 10.6). While they are comparatively inexpensive, the various penetrometers do not necessarily give the same numerical value if used on the same produce. Therefore, it is necessary to specify the instrument used when reporting pressure test values or attempting to set standards.

Chemical measurements

Measurement of chemical characteristics of produce is an obvious approach to the problem of determining maturity, particularly as they can often be directly related to the taste (e.g. sweetness, sourness) of produce. The conversion of starch to sugar during maturation is a simple test for the maturity of some apple cultivars. It is based on the reaction between starch and iodine to produce a blue or purple colour. The intensity of the colour indicates the amount of starch (Plate 4). Sugar is usually a major component of soluble solids in cell sap and can be measured directly by chemical means. However, it is much easier and just as useful to measure soluble solid concentrations in extracted juice with a refractometer. These devices operate on the basis of refraction of light in its passage through a thin sample of juice containing sugars, and variation in the density of juice according to its sugar content, respectively. Maturity standards for melons, grapes and citrus are often based on soluble solids concentration.

Acidity (titratable acidity) can be determined on a sample of extracted juice by titration with an alkaline solution (normally 0.1 N NaOH) to a colour change of a pH indicator (e.g. phenolphthalein) or to a specific pH (commonly 8.1). Loss of acidity during maturation and ripening is often rapid. The sugar/acid or total soluble solids/acid ratio is often better related to palatability of the fruit than either sugar or acid levels alone. Maturity standards for citrus fruits are commonly expressed as percentage soluble solids/acid ratios. A minimum soluble solids concentration is often included in specifications of citrus and pineapple fruits for processing and for grapes used for drying or juice production.

Dry matter content, which tends to increase as certain fruits mature, can be used for produce in which there is a large increase in the amount of starch or sugar as the fruits mature (e.g. kiwifruit and mangoes). Although dry matter content is most widely used for avocados, oil content can also be used as a maturity index for this compositionally unusual fruit.

Non-destructive methods for determining maturity and/or defects

Researchers are continually looking for improved ways to determine maturity. Similarly, the search for cost-effective methods of detecting defects, particularly internal defects, is continuing. Some non-destructive technologies which may in time find broader application include chlorophyll fluorescence spectrophotometers that can detect chlorophyll loss, and X-ray and magnetic resonance systems that are based on detecting differences in tissue density or proton mobility in tissue, respectively. The latter techniques can, for example, reveal the commencement of ripening in the inner mesocarp and/or internal cavities associated with the activity of fruit fly larvae in mango fruit. Like common measures of visible colour, X-rays and magnetic resonance (radio frequencies) utilise different parts

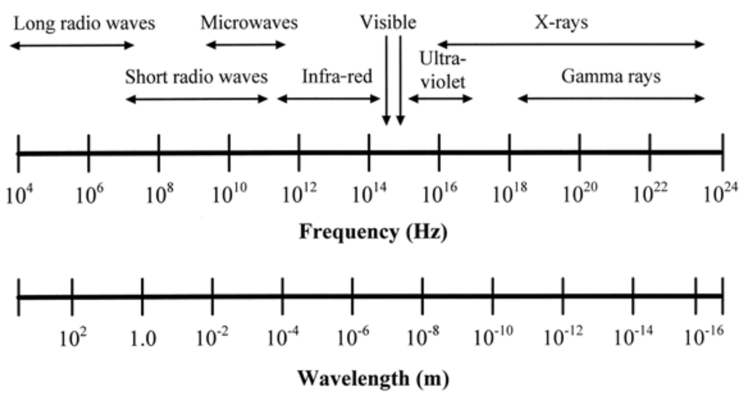


Figure 10.7 Electromagnetic spectrum illustrating the wavelengths of radiation that can be used for the non-destructive detection of changes in the structure and composition of plant tissues

of the electromagnetic spectrum (Figure 10.7). Near infrared spectroscopy utilises yet another portion of this spectrum, and is finding increasing application as a means for non-destructively determining sugar content in relation to harvest maturity or eating quality of crops such as melons. Molecular probes which bind to mRNA or proteins might be used to detect early biochemical changes during ripening (e.g. synthesis of ACC synthase or ACC oxidase). Finally, solid-state broadband sensors or biosensors may be applied to 'sniff' produce in order to detect the presence of volatiles associated with ripening, disorders or rotting.

Management of quality

The gradual breakdown of barriers to free international trade has led to the concept of the 'global village' in which fresh produce is able to move freely from country to country based on seasonality of supply and climatic conditions. Under these conditions, domestic markets in many countries are facing increased competition from imported products. Global trade is not new. For many years, tropical fruits such as bananas produced in areas like the Caribbean were transported by sea to Europe and North America. The freeing of international trade has led to a much stronger emphasis on quality assurance so that buyers can rely on produce specifications being consistent.

Each market has its own criteria for home consumption and for export, depending on local circumstances, but generally only the higher quality lines are exported because of the longer time the produce has to survive before consumption. Aspects of quality such as those outlined in the previous section are today considered primarily as commercial issues set by customers in order to procure the standard of produce required for an individual market. While in the past, specifications were often statutory requirements administered and enforced by government agencies, today in the majority of countries it is customers, often larger retailers, who are driving the development of produce specifications; since they are usually the final point of contact with consumers. Those customer specifications clearly define a set of produce attributes, packaging and labelling requirements and increasingly state the acceptable quality/food safety assurance systems under which produce must be grown or handled. In specifying system requirements, customers are establishing the mechanism through which the specification may be managed and enforced throughout the supply chain. While the focus continues to be on visual assessment, and advanced optical systems are now widely used for sorting produce for size, colour and surface blemishes, the application of technology relating to the non-destructive testing of internal quality attributes is now allowing far more accurate predication of quality aspects such as flavour and texture.

Government activity is now primarily restricted to the assurance of pest- and disease-free status for both domestic and export markets. For many years there has been a requirement for fresh produce moving between countries to be guaranteed free of certain pests and diseases. The governments of exporting countries are responsible for providing an inspection service and issuing the necessary phytosanitary certificates required by importing countries, as well ensuring that imported produce does not breach domestic quarantine requirements. Even within some countries such as Australia, interstate certification is also required for some produce moving into areas with pest-free status.

Quality systems

While quality may be considered a commercial factor, other aspects of produce assurance such as food safety are today considered fundamental to supply. Consumers expect that fresh produce will not contain pesticides and microorganism residues that can harm human health. In coming years, issues such as work health and safety (WHS or OHS), worker welfare, biosecurity and bioterrorism will become increasingly important 'tickets' to supply, providing for a 'total on-farm assurance package'.

Since the early 1990s, many horticultural industries have moved towards a holistic system in which quality is managed along the whole distribution chain, from the farm or orchard to the final point of sale. To achieve this, it is necessary to monitor and prevent quality problems as early as possible in the production process, rather than rely on endpoint and reactive inspection at a later stage during distribution when the produce has become more valuable. The assurance of quality is especially important where produce is shipped long distances and for long periods to overseas markets. While the implementation of quality assurance systems may entail some cost, ultimately a well-managed system acts to reduce costs by preventing quality problems and suppliers will gain a marketing advantage by providing buyers and consumers with the confidence that the produce consistently meets their specifications.

The early quality assurance systems in horticulture evolved from formal quality management systems/structures in other industries. The ISO 9000 series was used as the basis for early attempts at system development, but the rate of system uptake was slow. Today, the focus is on a risk management based approach, with the majority of the systems underpinned by the HACCP (hazard analysis and critical control points) technique. While conventionally used for food safety, HACCP is increasingly being used across a range of 'assurance areas', enabling individuals to assess risk and thus identify what might go wrong, establish controls to minimise the likelihood of such an occurrence and take corrective actions to manage those that do occur. The formal steps of HACCP are as follows: (1) identify and assess all hazards, (2) identify the critical control points, (3) identify the critical limits, (4) establish the monitoring procedures, (5) establish corrective actions, (6) establish a record-keeping system, and (7) establish verification procedures. This systematic approach has removed many of the concerns formerly associated with quality assurance systems.

Examples of this approach include EurepGAP which, as a HACCP-based prescriptive code, has in recent years become the recognised standard for growers supplying produce into the European market; or the BRC (British Retail Consortium) Standard, a prescriptive code developed for the supply chain post farm gate.

A key factor in the successful uptake of any assurance program is the mode of delivery. Experience has shown that the greater the involvement of the grower in training and in the implementation of the system, the more successful the outcome. In general, where systems are developed and implemented by an external consultant without focused client training or involvement, the ability of the client to successfully maintain that system is more limited.

Today, for most horticultural producers the record keeping required to maintain their chosen system is second nature and simply considered part of good business practice. Another important element in achieving and maintaining customer confidence is auditor consistency. Most customers require third party (independent) certification to a nominated system or standard. The majority of the 'System/Standard Owners' have clear requirements for auditor capability and experience.

The increasing number of assurance programs worldwide is driving the need for a recognition framework to be developed whereby individual standards organisations can be benchmarked to enable inter-country recognition without businesses requiring multiple certifications. This process has been initiated in part by programs such as EurepGAP and the Global Food Safety Initiative (GFSI), but there is still a long way to go before the global fresh produce industry can claim to have established consistent requirements and implementation across all markets.

11
Preparation for market

Preparing fruit and vegetables for market involves all handling operations from harvest until produce leaves the packinghouse. The main operational areas are harvesting, grading, pre-storage treatments and packaging. Control of disorders (Chapter 8) and diseases (Chapter 9) and evaluation and management of quality (Chapter 10) are discussed elsewhere.

Harvesting

Harvesting involves separation of produce from their vital sources of water and nutrients. Harvesting may also elicit wound responses such as increased ethylene production and respiration arising from the physical act of harvesting. Mature fruits generally show small responses to harvesting because they have stored carbohydrate reserves and relatively low respiration and transpiration rates and are destined for natural separation by abscission. However, rapidly metabolising tissues such as leafy vegetables generally exhibit more dramatic responses to harvesting. An important precaution at harvest is to avoid contamination of produce with both plant pathogens and more importantly animal and human pathogens.

It is usually best to harvest in the cool of the morning, when the heat load and hence produce metabolism and respiration is lowest. This is not feasible for around-the-clock mechanical harvesting of processing crops such as beans that need to make best use of expensive machinery and to meet factory processing schedules. Also, for some produce it is better to delay harvesting until the early morning dew is gone and fruit turgor is lowered. For example, in wet, damp, cool conditions the oil cells in the skin of oranges can be very turgid, and if the fruit are roughly handled the oil cells will burst. The release of the citrus oil causes the death of skin cells and a discolouration, known as oleocellosis.

Specific handling at harvest is required for mangoes as their sap contains a range of compounds such as terpinolene, which can stain and 'burn' the fruit surface. This degrades consumer acceptability of the fruit and encourages the growth of secondary pathogens to cause rots. De-sapping is a common postharvest operation in many mango cultivars that allows the latex sap to drain from the fruit. Removal of any sap residue from the skin can be achieved with specific detergents coated on the fruit surface followed by water sprays.

Numerous mechanisms and tools are available for the efficient harvesting and handling of fruit and vegetables. These include cutting with secateurs, mechanically shaking the tree and using long poles fitted with a cutter device for fruit on high trees. Motorised 'cherry pickers' with extendable arms that can support an operator and a picking bag are an extremely useful, albeit expensive, picking aid. Harvest platforms are also used in greenhouses to harvest vegetables such as cucumbers, where the plants are trellised. The harvest mechanism used largely depends on the strength of attachment of the organs, the degree of damage that is tolerable, and economic considerations. However, hand harvesting still predominates in most countries. In regions where labour costs are high, mechanical harvesting is used for robust, low unit value, ground crops such as potatoes and onions and for processing crops such as peas. Mechanical aids can be incorporated into hand harvesting; for example, conveyors used to move hand harvested pineapples and melons to bins mounted on a trailer moving parallel to picking rows, or platforms on which people lay or sit to gather strawberries. In addition, 'flying foxes' (overhead ropeways) to convey heavy banana bunches into the packinghouse in steep areas are used around the world. The ultimate in mechanisation is with lettuce grown on large farms, where harvesting, packing and cooling are all undertaken in the field.

It is important during harvest and handling to avoid physical injuries which encourage microbial growth and water loss. Apart from careful manual handling, the use of devices such as deceleration chutes to transfer fruit from picking bags to bins and lining picking bins and farm trailers with padding assist in minimising damage. Harvested produce should be kept as cool as possible by placing produce in the shade, using either natural shade (e.g. tree canopy) or covers such as tarpaulins. Minimising field heat is essential to maximising storage life and quality (Chapter 5).

Postharvest handling

Washing and brushing

Washing is essential to remove dirt and debris from produce after harvest. However, contaminated wash water is a carrier of plant and human pathogens. Pathogens can accumulate in the wash water and cross-contaminate all other produce passing through

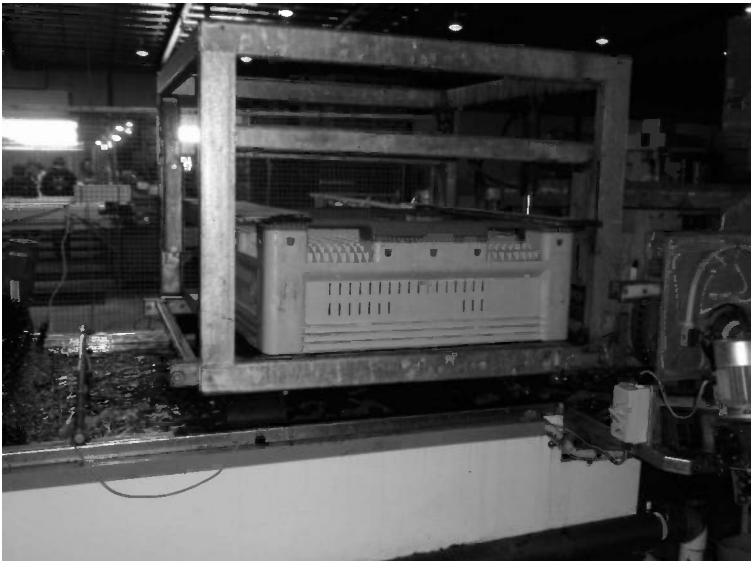


Figure 11.1 **Sanitised dump water is used to transfer cherries onto the packing line**

a dip tank. The correct use of sanitisers to decontaminate wash water is essential (Figure 11.1 and Plate 5). Food safety is fundamental to any postharvest practice, and the correct use of washing and sanitisers is critical to manage food safety risks.

A range of sanitisers is used in packing sheds. The advantages and disadvantages of the three most widespread sanitisers – chlorine, peroxyacetic acid and ozone – are presented in Table 11.1. Chlorine is the most commonly used sanitiser, either in the form of sodium or calcium hypochlorite. The main advantage of chlorine is that it is relatively inexpensive and has broad-spectrum effects. However, its effectiveness is dependent on the pH of the wash water, which needs to be maintained between 6.5 and 7.5, and its concentration needs to be constantly monitored.

Table 11.1 Advantages and disadvantages of common postharvest sanitisers

Chemical	Advantages	Disadvantages
Chlorine	Available in different forms Broad spectrum Relatively inexpensive	pH affects activity Organic matter affects activity Corrosive to equipment
Peroxyacetic acid	Good stability Broad range of pH Works well in cold conditions	Less corrosive to equipment Difficult to monitor More expensive than chlorine
Ozone	High efficacy Breaks down to oxygen Less sensitive to pH than chlorine	Organic matter affects activity Highly corrosive Must be generated on-site Can be harmful/toxic to humans

Peroxyacetic acid (peracetic acid) is growing in popularity because of its effectiveness and environmental compatibility. It is generally used at 50 to 80 microlitres per litre and is highly effective against a broad spectrum of bacteria and fungal spores. Ozone (O_3) is a very strong oxidising agent but it is highly corrosive. It must be generated *in situ* as it has a very short half-life and concentrations need to be maintained below prescribed human toxicity levels. Other sanitisers include organic compounds which contain bioflavonoids and organic acids, gas based sanitisers (such as chlorine dioxide), and systems such as bromo-chlorodimethyl hydantoin and electrified oxidising water.

Brushing is often used in conjunction with washing to assist in the removal of contaminants, including insects, on the surface of produce. This can also be achieved with high-pressure washers which can also help remove chemical residues. The use of postharvest fungicides is an integral component in many handling systems (Chapter 9) and is generally applied after washing. However, some fruit, such as strawberries and tomatoes,

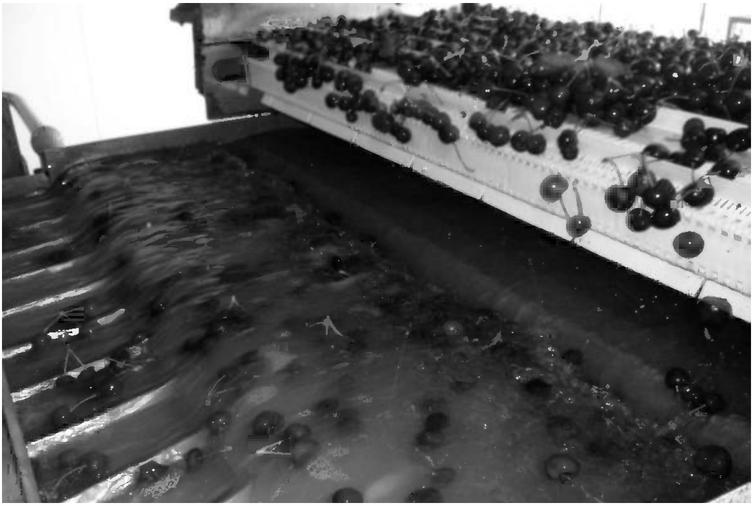


Figure 11.2 **Water transfer of cherries in a grading line.** Chilled sanitised water moves the fruit through the grading line.

are generally not washed before market, which necessitates good field hygiene to prevent any food safety concerns.

Grading

Grading is an important process, as the presentation of fruit and vegetables is often judged in the market on the basis of uniformity. Fruit and vegetables can be moved through a packing and grading line on rollers or through sanitised water transfer (Figure 11.2, Plate 6). Fruit and vegetables are generally graded on the basis of size, weight, colour, defects or composition, or a combination of these features; and there is a range of commercial grading systems which are often mandated by the customer.

Older-style size graders for fruit separate produce using diverging conveyor belts, which segregate fruit based on increasing size. Computerised weight graders can also operate on the basis of tipping buckets, which drop to release the pre-weighed item at a particular position. However, image capture is now regularly used for size, and colour grading and detecting external defects such as surface blemishes. Advanced neural network analyses and algorithms can now be used to determine whether any given image feature, such as presence of a stalk or size of a skin blemish, is acceptable or unacceptable. High-speed cameras analyse produce as it passes over conveyor rollers which rotate the fruit passing through the camera's field of vision, coupled with the use of side mirrors so that all sides of a fruit are imaged. A wide range of fruit and vegetables now have specialised commercial graders including citrus, apples, peaches, cherries, kiwifruit, carrots, capsicum and onions (Plates 7 and 8).

In addition to external quality measured with standard high-speed cameras which use the visible light spectrum (400–700 nm), the near infrared (NIR) spectrum (700–2500 nm) is also used to sort internal quality as radiation in this spectrum can penetrate produce. NIR sorting is routinely used to measure total soluble solids and dry matter present at per cent levels. The commercial application of this technology has led to the consistent grading and marketing of premium quality produce with consistent lines of guaranteed levels of sweetness. Another promising application of NIR is in the detection of the severity of internal defects such as internal browning in apples, granulation in citrus and internal browning in kiwifruit. The use of NIR spectroscopy on the packing line is expensive to apply, but it allows the accurate removal of inferior fruit. Although there are some limitations to NIR spectroscopy, the evolution and improvements in the availability and reliability of this and other technologies such as multispectral and hyperspectral imaging will make non-destructive sorting even more commercially applicable.

Other technologies commercially available to non-destructively sort horticultural produce include the use of force-deformation where an impact system with an accelerometer assesses the de-acceleration rate of a light object striking the surface of the fruit. An air-actuated bellows (as used in many fruit labelling systems) carries the accelerometer into contact with the fruit. However, such acoustic measures have had limited commercial success. Technologies with potential application in grading include X-ray imaging and tomography, proton or chemical shift magnetic resonance imaging, transmitted and reflected light spectroscopy, acoustic response signals to tapping, and volatile emissions analysis using solid-state detectors (Chapter 10). However, such advanced technologies are not likely to find practical application until their capital cost is minimised. There is an ever-present need to grade out sub-standard produce on the basis of internal defects in more complicated systems such as pineapples, and the presence of quarantine pests and the need to not only sort for total soluble solids but eating quality including flavour.

Postharvest treatments

Waxing

Many countries allow food-grade waxes to be applied to fruit and vegetables, such as apples and oranges, to reduce water loss and increase consumer appeal. The rate of water loss can be reduced by 30–50 per cent under commercial conditions, particularly if the stem scar and other injuries are coated with wax. In many countries, citrus fruits are commonly waxed because washing and brushing can remove much of the natural wax from the peel, thereby increasing fruit shrivel and loss of good appearance.

Most commercial wax formulations contain a mixture of different waxes derived from plant and/or petroleum sources. Many have been based on a combination of paraffin wax (which gives good control of water loss but a poor lustre to produce) and carnauba wax (which imparts an attractive lustre to the produce but poorer control of water loss). In addition, formulations containing polyethylene, synthetic resin materials, sugars and sugar derivatives, chitosans, and emulsifying and wetting agents have been used. In some instances, the wax formulation may be used as a carrier of fungicides and inhibitors of senescence and sprouting. Waxes are brushed, dipped, sprayed, fogged or foamed onto produce. It is important that the wax film is thin or else gas exchange may be overly hindered, causing anaerobiosis and associated quality loss such as off-flavours.

Curing

Underground storage organs such as potato and sweet potato tubers tend to have poorly developed cuticles and are therefore relatively susceptible to mechanical wounding during harvesting and handling and to postharvest water loss and decay. These problems can be minimised by the process of 'curing' at intermediate to high temperatures and high humidity before regular storage. For example, sweet potatoes can be cured at 30°C and 90–95% RH for 4–7 days prior to storage, and potatoes at 10–15°C and 95% RH for 10–14 days. During curing, a surface layer of protective suberised wound periderm tissue (Chapter 2) is formed over the produce, especially at wound sites. Although most rapid periderm formation on potatoes occurs at about 20°C, the risk of decay at this comparatively high temperature is unacceptable. Curing treatments may also facilitate wound healing for certain fruits such as citrus.

Sprout inhibitors

The buds of potatoes and onions enter a dormant state at maturity and these items can be stored for many months under correct conditions for either retail marketing or processing. The duration of postharvest dormancy (rest period) of potato tubers is influenced by maturity and cultivar but generally not by the storage temperature. Once the rest period ends, the rate of sprouting is dependent on temperature. Sprouting of potatoes rarely occurs below 4°C, but storage at these temperatures is impractical due to the conversion of starch to sugars (Chapter 4). Sprouting at temperatures greater than 4°C is a problem during storage periods greater than 2–3 months.

The application of several chemicals and ionising radiation (see later in this chapter) effectively suppress sprouting in potatoes and onions during storage at higher temperatures. However, legal restrictions on the usage and permitted residues of these compounds vary among countries. 3-Chloroisopropyl-N-phenylcarbamate (CIPC) is a strong sprout inhibitor and is probably the most widely used chemical for the storage of potatoes. CIPC may be applied as a dust, water dip, vapour or aerosol. Like many of the other chemical sprout inhibitors, CIPC interferes with periderm formation and thus should be applied after curing (see above). Sprouting of onions during long-term storage is effectively prevented by maleic hydrazide applied several weeks before harvest. Although chemical anti-sprouting agents are effective, industry is looking at alternative non-synthetic chemical treatments such as essential oils, ethylene and controlled atmospheres to manage sprouting.

Controlled ripening

Some climacteric fruit, such as bananas, European pears, kiwifruit and mangoes, are harvested at a green mature stage or before fully ripe and are transported often over considerable distances to consumers. These fruits are then ripened to optimum quality under controlled conditions of temperature and humidity and with some fruits through the addition of ethylene and other gases which initiate ripening. This allows fruits to be transported when they are less susceptible to bruising and other types of damage. A further advantage of controlled ripening is improved uniformity of ripening among fruits. In contrast, non-climacteric fruits do not undergo substantial desirable changes in composition after harvest and are therefore harvested when they are at their optimum quality for consumption.

Most of the world production of bananas is ripened under controlled conditions. The banana is unusual in that it can be picked over a wide range of physiological maturity stages, from half-grown (thin and angular) to fully grown (full and rounded), and ripened to high quality with the aid of ethylene. As discussed in Chapter 6, ethylene is the natural ripening hormone and is by far the most active of the known ripening gases.

Acetylene can be generated by adding water to calcium carbide, which also induces the ripening response, but a concentration at least 100 times higher than ethylene is required. However, the use of carbides is banned in many countries due to health concerns.

The commercial ripening of bananas is a routine operation and fruit at a specified colour stage (Table 11.2, Plate 9) can be produced on a predetermined schedule. The effective concentration of ethylene for banana ripening is quite low (Table 11.3) and when this concentration is maintained for the stated period, further increases in concentration give no added advantage. In practice, however, high concentrations are used initially because the ripening rooms are often not sufficiently airtight. Bananas may be ripened in a batch process in which the chamber (Figure 11.3) is charged (the 'shot') with ethylene gas to a concentration of between 20 and 200 microlitres per litre. The ripening chamber has to be ventilated after the first 24 hours to prevent the accumulation of carbon dioxide. Carbon dioxide concentrations should not exceed 5000 microlitres per litre (0.5 per cent) to allow workers to enter the rooms to inspect the fruit. If the chamber is poorly sealed, it may be necessary to recharge with ethylene after 12 hours. A satisfactory alternative to charging the ripening chamber with an initial high concentration of ethylene is to 'trickle' ethylene into the chamber (Figure 11.4) at a rate just sufficient to maintain the concentration shown in Table 11.3. Ripening chambers should be ventilated at the rate of about one room volume each 6 hours to prevent the accumulation of carbon dioxide.

Water loss can be high at ripening temperatures unless a high humidity is maintained. Humidity can be raised by atomising water into the ripening chamber. For bananas, an RH of

Table 11.2 Colour stages of the ripening Cavendish banana

Stage	Peel colour	Starch (%)	Sugar (%)	Comment
1	Green	20	0.5	Hard, rigid; no ripening
Sprung	Green	19.5	1.0	Bends slightly, ripening started
2	Green, trace of yellow	18	2.5	
3	More green than yellow	16	4.5	
4	More yellow than green	13	7.5	
5	Yellow, green tip	7	13.5	
6	Full yellow	2.5	18	Peels readily; firm ripe
7	Yellow, lightly flecked with brown	1.5	19	Fully ripe; aromatic
8	Yellow with increasing brown areas	1.0	19	Overripe; pulp soft and darkening, highly aromatic

Table 11.3 Ripening conditions for some fruits using ethylene

Fruit	Temperature (°C)	Ethylene (μL/L)	Treatment time (hours)
Avocado	18–21	10	24–72
Banana	15–21	10	24
Cantaloupe	18–21	Nil	
Honeydew melon	18–21	10	24
Kiwifruit	18–21	10	24
Mango	29–31	10	24
Papaya	21–27	Nil	
Pear	15–18	10	24
Persimmon	18–21	10	24
Tomato	13–22	10	Continuously

Figure 11.3 **A modern double-deck controlled ripening room for bananas using forced-air circulation.** The boxes are vented to allow air to be drawn through the packed fruit.

85–90% has been recommended for ripening to stage 2, but this should be reduced to 70–75% during the later colouring stages to avoid skin splitting. Although the best skin colour may be achieved at the highest RH, commercial experience has shown that the skin tends to be too soft and may split, while

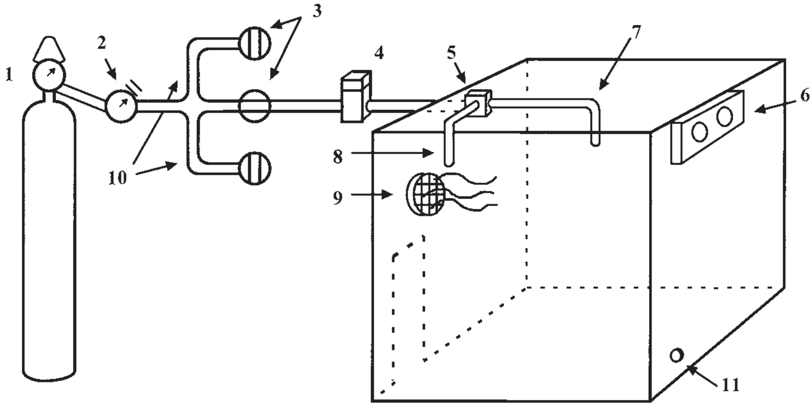


Figure 11.4 Trickle system for adding ethylene to a ripening room. (1) ethylene cylinder; (2) pressure regulator with outlet pressure set on 300 kPa; (3) on-off toggle valve; (4) solenoid valve wired to open only when the air circulation fan is operating; (5) variable flow controller or rotameter located on the front wall of the room; (6) air circulation fan or refrigeration unit; (7) gas outlet located near the centre of the room in small rooms (less than 60 m^3); (8) in larger rooms, the gas outlet is located in front of the outlet from the blower fan; (9) blower fan mounted on the front wall of the room (the amount of air discharged into the room can be regulated to provide a predetermined rate of ventilation); (10) branches to other rooms if required; (11) a small exhaust porthole is provided in the rear wall of rooms (usually large rooms over 60 m^3) that require mechanical ventilation.

SOURCE W.B. McGlasson, E.E. Kavanagh and B.B. Beattie (1986) 'Ripening tomatoes with ethylene', *Agfact* H8.4.6, NSW Department of Agriculture, Sydney.

if RH is too low, weight loss may be excessive, colour poorer and blemishes more pronounced. Because of the high RH and temperature maintained in ripening rooms, moulds can grow on the walls of the room which then need to be sanitised.

The use of ethylene to ripen other climacteric fruits that have been harvested immature generally produces ripened fruits of inferior quality to those harvested at the mature green stage. With many of these fruits it is more important to harvest at the correct stage of maturity. For example, the optimum maturity is the full-slip stage for cantaloupes, the first appearance of yellow colour in the blossom end of papayas, and the first colour (breaker) stage of tomatoes. At full maturity, it is only necessary to hold produce at the temperature and humidity specified in Table 11.3 to achieve high quality ripened fruit – treatment with ethylene is not necessary. When fully developed, at least some (if not all) of the fruit will produce sufficient ethylene to effectively ripen themselves and adjacent fruit. Nonetheless, ethylene treatment will promote more uniform and rapid ripening in consignments of mixed maturities (e.g. from once-over [strip] picked mango fruits).

Controlled degreening in citrus

The pulp of many early-season citrus cultivars becomes edible before the green colour has completely disappeared from the peel. Exposure to low temperatures in the orchard during maturation is necessary for the development of an orange-coloured peel. This requirement means the peel of citrus grown in the low altitude tropics fails to completely degreen. Furthermore, the Valencia orange cultivar is often stored on the tree for several months after ripening has been completed, and during this storage period the peel tends to regreen.

Postharvest treatment with ethylene under controlled conditions hastens the loss of chlorophyll. This process is known as degreening. Batch or trickle degreening is a cosmetic treatment designed to give the fruit a ripe appearance but does not result in significant changes in pulp composition if correctly administered. The conditions of batch degreening, 20–200 microlitres ethylene/litre at 25–30°C and 90–95% RH, are maintained for 2–3 days with regular ventilation of the chamber to prevent build-up of carbon dioxide (citrus is injured by CO_2 concentrations above 1 per cent). Trickle degreening, with 10 microlitres ethylene/litre continuously metered into the room, is more rapid than batch degreening and is therefore preferable since degreening conditions accelerate deterioration and decay of citrus. Although the most rapid degreening occurs at 25–30°C, production of peel carotenoids is greatest at 15–25°C.

In some citrus growing areas, notably Florida in the USA, tangelos, temples and some early season oranges, do not experience enough cold weather to promote the development of a highly coloured peel. Packinghouses in these areas have been legally permitted to dye the peel of these fruits under strictly controlled conditions with Citrus Red No. 2 (1-(2,5-dimethoxyphenylazo)-2-naphthol) and all fruit must be labelled to reflect this treatment. After treatment, the fruit are rinsed thoroughly to prevent 'bleeding' of the dye through the wax and to ensure a residue tolerance of 2 mg/kg fruit is not exceeded. Wax is then applied after all the surface water has evaporated.

Packaging

Packaging of fruit and vegetables is essential to get the produce in good condition to the consumer and has been practised for as long as fresh produce has been traded. The two main functions of packaging are to assemble the produce into convenient units for handling (unitisation) and to protect the produce during distribution, storage and marketing (protection). However, more recent functions of packaging have included marketing and consumer information.

Packages and packaging for fresh produce need to meet a range of basic requirements. For example, they must:

- have sufficient mechanical strength to protect the contents during handling and transport, and while stacked
- be largely unaffected, in terms of mechanical strength, by moisture content when wet or at high humidity
- stabilise and secure produce against movement within the package during handling
- not contain chemicals which could transfer to the produce and taint or be toxic to the produce or humans
- meet handling and marketing requirements in terms of weight, size and shape
- allow rapid cooling of the contents and/or offer a degree of insulation from external heat or cold
- utilise gas barriers (e.g. plastic films) with sufficient permeability to respiratory gases as to avoid any risk of anaerobiosis
- offer security for the contents and/or ease of opening and closing in some marketing situations
- provide handling and consumer advice by identifying the contents, suggest handling instructions and aid retail presentation
- either exclude light (e.g. from potatoes) or be transparent (e.g. strawberry punnets)
- facilitate easy disposal, reuse or recycling
- be cost-effective in relation to the value and the required extent of protection of the contents.

Prevention of mechanical damage

Fruit and vegetables vary widely in their susceptibility to mechanical damage and in the types of mechanical injury to which they are susceptible. Accordingly, the choice of package and packing method must take these differences into account. Four different causes of mechanical injury to produce can be identified: vibration, compression, impact and cut. The relative susceptibilities of some fruits to compression, impact and vibration injuries are shown in Table 11.4.

With the possible exception of certain so-called 'hard' vegetables, such as watermelons, pumpkins, onions, carrots and potatoes, the package must be strong enough to carry stacking loads otherwise there will be compression bruising of the contents. Plate 10 shows the use of different packaging types for pumpkins, melons and oranges. Impact bruising is caused by dropping packages and by other impact shocks during handling (e.g. on the grading line) and transport. Bruising is tissue damage which results from strain energy being dissipated in the tissue – the amount of damage depends on how much energy is dissipated and the nature of the tissue. Vibration injury is common during transport and results in abrasion marks ranging from light rub to removal of the skin and possibly some of the flesh. The problem of cuts (e.g. from sharp edges) and punctures (e.g. stem punctures) also merits attention.

Nearly all mechanically damaged tissue turns brown through enzymatic (e.g. polyphenol oxidase) or chemical (atmospheric oxygen) oxidation of phenols. Tissue deformation and browning is exacerbated by increased water loss as a result of damage to the cuticle. Furthermore, injuries represent sites for microbial infection in terms of both damage to the

Table 11.4 Susceptibility of produce to types of mechanical injury

Produce	Type of injury		
	Compression	Impact	Vibration
Apple	Susceptible	Susceptible	Intermediate
Apricot	Intermediate	Intermediate	Susceptible
Banana, green	Intermediate	Intermediate	Susceptible
Banana, ripe	Susceptible	Susceptible	Susceptible
Cantaloupe	Susceptible	Intermediate	Intermediate
Grape	Resistant	Intermediate	Susceptible
Peach	Susceptible	Susceptible	Susceptible
Pear	Resistant	Intermediate	Susceptible
Plum	Resistant	Resistant	Susceptible
Strawberry	Susceptible	Intermediate	Resistant
Tomato, green	Susceptible	Intermediate	Intermediate
Tomato, pink	Susceptible	Susceptible	Intermediate

SOURCE R. Guillou (1964) 'Orderly development of produce containers', *Proceedings of the Fruit and Vegetable Perishables Handling Conference*. University of California, Davis, CA: 20–25.

protective skin and the release of substrates for growth (e.g. sugars). The physiological wound response involves increased ethylene production and respiration and hence acceleration in the rate of produce deterioration.

Two important practical requirements must be met when packaging fruit and vegetables. These are that individual items should not be allowed to move with respect to each other or to the walls of the package in order to avoid vibration injury, and the package should be full without being packed too tightly, which increases compression and impact bruising. Plate 11 shows a cut-away of a fibreboard apple box with fibreboard trays holding the apples in place to prevent their movement and bruising. Note the use of bubble wrap on top of the box to minimise any compression damage.

Packaging can be made more protective by individually wrapping each piece of product (e.g. paper wraps), by isolating each piece (e.g. cell and the tray packs), or by use of energy absorbing materials (e.g. cushioning pads and bubble wrap). However, such additional packaging increases costs and must therefore be justified by reduced wastage, increased selling price, or establishment of a reputation for reliable quality such that price and sales are maintained during periods of over-supply. Careful handling of the packages is the best general precaution against mechanical damage.

Cooling produce in the package

An important requirement of packaging is that it allows rapid cooling of produce. For example, containers designed for pressure cooling (Chapter 4) should have holes which occupy about 5 per cent of the surface area on each of the air entry and exit ends. Both the nature of the produce and the treatment after packing must be considered in designing containers for specific commodities. Ideally, respiratory heat should be able to escape readily from the package. In the case of small and/or tightly packed commodities such as green beans, small fruits and leafy vegetables, the vital heat of respiration is removed largely by conduction to the surface of the package. Therefore, the mass of the contents (i.e. the minimum dimension of the package from the centre to the surface) becomes a critical issue. The acceptable mass depends on the respiration rate of the commodity. If the mass of produce is excessive, the centre of the package will heat up because respiratory heat cannot dissipate fast enough. This problem may be avoided with smaller packages or by ventilating large packages or stacks.

Effect of packaging on weight loss

Packaging is often used to minimise weight loss and shrinkage of fruit and vegetables during marketing. Specific introductions include waxed paper or plastic film wrapping or bagging of individual items, consumer packaging of a number of items in trays overwrapped with a moisture barrier material, and increasing the moisture resistance of fibreboard packages with a surface or internal plastic laminate or by lightly or fully waxing the carton. In addition, under dry conditions pallets or crates of produce may be deliberately sprayed with water. Direct wetting can also assist in cooling produce through evaporation of the added water.

Water loss in packages can be reduced by the use of micro- (pin-hole size) or macro-perforated films. However, the build-up of condensation within moisture barriers can become a problem if there is poor temperature management. Chemical anti-fogging treatments can be applied to films, and films with relatively high water permeability can be used (e.g. cellophane, polyvinylchloride). Importantly, precautions to avoid condensation must also maintain product visibility (e.g. berry fruit in overwrapped punnets). Water-absorbent pads can be used at the bottom of packages to capture and hold the free water resulting initially from condensation.

Package dimensions

Package dimensions are both economically and structurally important. Packages should offer adequate strength and allow easy and secure handling, loading and stacking. An optimal length to width ratio is about 1.5:1. There is a trend to use smaller packages for ease of handling. Thirty litre (about 20 kg of produce) and 15 litre packages are becoming standard for fruits, with larger 36 litre packages being used for some vegetables. Retail-ready packages of fruit may contain only 5 kg of fruit in a single layer. Standardisation of package sizes promotes efficient handling. Package sizes are standardised by determining dimensions and numbers that fit well on standard pallets.

Mechanical strength of the package

For continued protection of produce against damage, packages must retain their strength throughout the marketing chain. Wood and solid and expanded plastic packages are inherently strong, compared to fibreboard packages. However, wood is an expensive and environmentally costly material. Solid plastic containers are even more expensive, but they are amenable to washing and reuse. Rigid expanded polystyrene is light weight but strong and a good insulator, but it requires considerable storage space and has recycling problems (Chapter 12). In comparison, fibreboard is attractive and can be made stronger by the use of two or more thicknesses, such as the bottom and lid of fully telescoping cartons. The strength of fibreboard lies in the fluting between the inner and outer liners. Fibreboard comprised of two layers of fluting sandwiched between three liner layers is stronger than the conventional single layer of fluting.

Under conditions of high humidity, after condensation or after being wet by rain, the strength of the package should either be independent of moisture content (e.g. wood) or the package material should not absorb moisture (e.g. plastic). Commonly used fibreboard cartons and trays rapidly lose strength as they absorb moisture and so are less than satisfactory under tropical conditions and in high humidity cool storage (Figure 5.3). However, fibreboard can be protected if fully impregnated with wax or similar material, although wax impregnation is expensive and waxed fibreboard is not recyclable. The corrugated fibreboard used in cartons is often only given a surface coating, which affords only a degree of protection from free water or high humidity.

Packing

The desirable pack for most fruit and vegetables is one in which the package is tightly filled, but not underfilled or overfilled, so that produce does not move and sustain vibration injury during handling and transport. Some produce, such as potatoes, carrots and oranges, will withstand reasonable compressive loads. These can be satisfactorily packaged in non-rigid packages, such as mesh bags, provided that they are handled with due care.

Fruit has traditionally been place- or pattern-packed such that each piece was put into a specific position with the aim to maximise net weight, maintain a tight pack and present the fruit attractively when the package was opened. Pattern packing machines are now widely used. Individual wrapping of fruit and vegetables still has a place, as does lining the package with plastic or paper in order to reduce vibration damage and/or moisture loss. Indeed, very delicate fruits, such as ripe papayas, may be sleeved in a thick spongy plastic mesh.

Plastic films for packaging produce should ideally have good tensile strength, gas and water permeability, clarity, printability and be heat sealable. Manufacturers can now develop a film to suit any nominated specification. Low-density polyethylene film is most widely used for consumer packs. Polyethylene has good clarity, can be heat sealed, is flexible over a wide temperature range (–50 to 70°C) and is probably the cheapest film in most countries. Polyethylene is also relatively permeable to many volatile compounds and gases but is comparatively impermeable to water vapour. Gas permeability of films can be controlled by varying either the density of the film or its thickness, or, as mentioned above, the film may be perforated.

It is not practical to recommend specific packages for each fruit or vegetable, as several types may be satisfactory. The most suitable package would depend on many factors, including the region, environmental conditions, length and nature of the market chain, methods of handling and transport, availability and cost of materials, and whether the produce is to be refrigerated.

Modified atmosphere packaging

As discussed in Chapter 7, many fruit and vegetables benefit from storage at low oxygen and high carbon dioxide levels. These atmospheres can be generated by the respiration of the produce within a sealed bag, which is balanced by permeability of the film, its thickness and holes in the film. Oxygen and carbon dioxide flux through holes is proportionally greater in magnitude than water vapour and ethylene flux because they are driven by comparatively large concentration gradients (i.e. per cent versus μL/L). Thus, perforated films can be used to reduce water loss while avoiding the risk of anaerobiosis.

All other factors being equal, oxygen diffuses somewhat faster in air (e.g. through holes in a film bag) than carbon dioxide on account of its greater diffusion coefficient. In contrast, all plastic films are relatively more permeable to carbon dioxide than oxygen. The lack of temperature control during handling and differences in the temperature quotient for physical gas diffusion across plastic films as compared to those for physiological processes such as respiration, increase the likelihood that anaerobic conditions may occur in sealed plastic film packages. In the future, such risks may be minimised in commercial packaging using fail safe (e.g. low melting point polymers) or variable aperture (e.g. bimetallic strips) devices to regulate the formation and/or size of holes. Advances in microelectronic, biosensor and polymer science areas are likely to produce films that actively sense and respond in a controlled way to stimuli such as an increase in temperature.

Recent trends in packaging materials

The earliest packages were mostly constructed of plant materials, such as woven leaves, reeds and grass stems (Figure 11.5), and were designed to be carried by hand. Even today, most packages are handled manually at some stage and are sized accordingly but are usually assembled into larger units for mechanical handling by forklift (e.g. pallet loads). Fruit and vegetables are now transported and sold in a wide range of packages constructed of wood, fibreboard, jute (hessian) or plastics (Figures 11.6, 11.7 and 11.8).

Figure 11.5 Typical bamboo baskets used for handling and transporting of produce

Figure 11.6 Jute bags of onions on pallets

Figure 11.7 **Wooden boxes for transport of mangoes**

Figure 11.8 **Palletised boxes of cherries ready for market**

The standardisation of packaging as a means of reducing waste of materials and to reduce costs has been recognised by supermarket chains. This has led to adoption of fibreboard trays with a standard 'footprint' that fully utilise the area of the standard pallet, especially for fresh fruit. The packed fruit are placed directly on retail display (retail ready), eliminating handling by store staff to stack displays. Unitisation of pallets and mechanical handling by forklift vehicles make standardisation essential for economical operation.

Solid plastic returnable crates are becoming increasingly common in closed-loop horticultural supply chains such as in retail markets. Crates are made of recyclable plastics, are not affected by humidity and provide complete protection for produce. Several types of fold-down or collapsible crates have gained acceptance as they only occupy a small amount of space for the return journey from the retailer to the distributor (Figure 12.2). A major benefit of such crates is the interlocking design that allows efficient stacking on a pallet and load stabilisation over long distances.

Traditionally, horticultural produce was sold to the market in bulk lots/cartons and sold in open retail displays for consumers to select what they required. However, a growing trend in many retail markets is pre-packaging, where individual produce are packed into smaller sealed units such as punnets, clamshells, overwraps, display boxes or bags. Pre-packs can be prepared at the packinghouse or by secondary processors close to the market. Pre-packaging also allows package space to provide consumer information such as handling and usage instructions and promotional labelling. However, pre-packing does not allow the consumer to select different individual fruits or vegetables and many consumers are resistant to excessive packaging.

Most packaging plastics are derived from petroleum sources, but environmental and sustainability issues have promoted interest in polymers derived from biological materials such as cellulose, starch and proteins. Polymers derived by bioengineering of waste materials are also being developed (Chapter 12).

Market access

Postharvest disinfestation

To prevent the movement of quarantine insect pests (such as tephritid fruit flies) and to facilitate trade between countries (and sometimes even within a country) that do not have these pests, an approved postharvest disinfestation treatment that kills 100% of these pest insects within the produce needs to be applied. Table 11.5 lists some important quarantine pests, their distribution and hosts. Note that this list is not comprehensive, as there are hundreds of pests of concern from many countries. Plate 12 illustrates two quarantine pests which restrict trade in many parts of the world.

Fumigation with gaseous chemical sterilants has been the most effective technique for disinfesting produce. However, they are increasingly unpopular (or banned) because of high mammalian toxicity (e.g. hydrogen cyanide), flammability (e.g. carbon disulphide) or damage to the environment (e.g. methyl bromide). Indeed, methyl bromide has been the most widely used fumigant but it damages the atmospheric ozone layer. There is a scheduled phase-out of methyl bromide usage but since there is no equally effective replacement, its use continues to be allowed for quarantine purposes only. The search for methyl bromide replacements has been exhaustive but no

Table 11.5 Some insects and mites that can be carried by fruit and vegetables

Insect	Common name	Common hosts	Approximate distribution
Fruit flies			
Anastrepha fraterculus (Wiedemann)	South American fruit fly	Mango, apple, peach, guava, citrus	South and Central America, Caribbean
Anastrepha ludens (Loew)	Mexican fruit fly	Citrus, mango, other tropical and subtropical fruits	Central America, Mexico, Caribbean
Bactrocera dorsalis (Hendel)	Oriental fruit fly	Wide range of fleshy fruits	Asia, Hawaii
Bactrocera tryoni (Froggatt)	Queensland fruit fly	Many deciduous and subtropical fruits	Australia, Pacific Islands
Ceratitis capitata (Wiedemann)	Mediterranean fruit fly	Deciduous and subtropical fruits, especially peach and citrus	Southern Europe, Africa, Central and South America, Hawaii
Ceratitis rosa (Karsch)	Natal fruit fly	Many deciduous and subtropical fruits	Africa
Dacus ciliatus (Loew)	Lesser pumpkin fly	Cucurbits	Africa, India, Pakistan, Bangladesh
Drosophila suzukii (Matsumura)	Spotted wing drosophila	Many deciduous fruits	Asia, parts of Europe and North America
Rhagoletis cingulata (Loew)	Cherry fruit fly	Cherry	North America
Mites			
Halotydeus destructor (Tucker)	Red-legged earth mite	Leafy vegetables	Australia, New Zealand, parts of Africa

Insect	Common name	Common hosts	Approximate distribution
Panonychus ulmi (Koch)	European red mite	Apple and other deciduous fruits	Europe, Africa, Asia, Australia, New Zealand, North and South America
Mealy bugs			
Dysmicoccus brevipes (Cockerell)	Pineapple mealy bug	Wide range including pineapple	Africa, Asia, Australia, South America
Planococcus citri (Risso)	Citrus mealy bug	Wide range including citrus, grape	World wide
Moths			
Thaumatotibia leucotreta (Meyrick)	False codling moth	Citrus, avocado, stonefruits, guava	Africa
Lobesia botrana (Denis & Schiffermüller)	Grape berry moth	Grape	Europe, Africa, Central Asia
Maruca vitrata (Fabricius)	Bean pod borer	Legumes	Africa, Asia, Australia, Central and South America, Pacific Islands
Scale insects			
Aonidiella aurantii (Maskell)	Red scale	Citrus	World wide
Lepidosaphes beckii (Newman)	Purple scale	Citrus	World wide
Quadraspidiotus perniciosus (Comstock)	San José scale	Deciduous fruits	World wide
Weevils			
Cylas formicarius (Fabricius)	Sweet potato weevil	Sweet potato, taro	Africa, Asia, Pacific Islands, North and South America

(*continued overleaf*)

Insect	Common name	Common hosts	Approximate distribution
Naupactus leucoloma (Boheman)	White fringed weevil	Root vegetables	South America, South Africa, Australia, New Zealand, USA
Sternochetus mangiferae (Fabricius)	Mango seed weevil	Mango	Africa, Asia, Australia, Caribbean

SOURCE Centre for Agriculture and Bioscience International (CABI) Invasive Species Compendium ◂www.cabi.org▸.

equally effective treatment has yet been identified. Fumigants such as high purity phosphine are in use while the use of less toxic generally regarded as safe (GRAS) chemicals, such as ethyl formate, have found some limited applications. In addition, high carbon dioxide and/or low oxygen atmospheres have been investigated as alternatives to chemical fumigants.

Attention has also focused on the development of physical postharvest disinfestation treatments. The most widespread non-chemical disinfestation treatment is cold temperature, as many insects such as fruit flies do not tolerate prolonged exposure to low temperature. This has led to an effective disinfestation treatment for many fruit and vegetables such as citrus fruits. Cold storage at less than 1.6°C for 16 days has been shown to disinfest fruit against many fruit flies such as Mediterranean fruit fly (*Ceratitis capitata*). However, many fruit and vegetables of tropical and subtropical origin are susceptible to chilling injury in response to extended cold treatment (Chapter 8) and for these produce, cold disinfestation cannot be used as a quarantine treatment.

Some horticultural produce can also be successfully disinfested by a short exposure to high temperature. High temperature treatments can be achieved with hot air, including vapour heat (Figure 11.9) or hot water. Vapour heat treatment is an approved quarantine treatment in some countries where, for example, the temperature of mangoes is raised to 47°C with air saturated with water vapour, and the core temperature of the fruit is maintained at that elevated temperature for 15 minutes. Other heat treatments include forced hot air and hot water treatments and, as with low temperature disinfestation treatments, the precise temperature treatment regime, the commodity type, pest and specific methods must be via negotiated agreement between the exporting and importing countries. As expected, not all fruit and vegetables can tolerate such

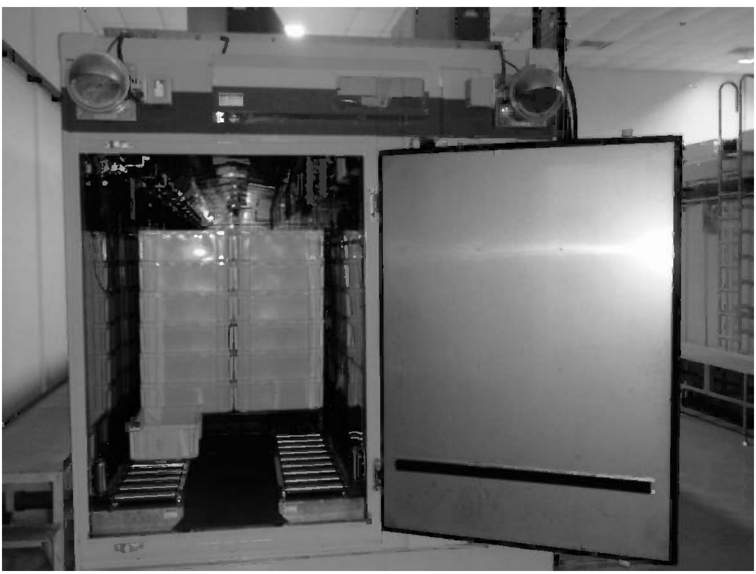


Figure 11.9 Commercial vapour heat treatment unit used to disinfest mango fruit

high temperature stresses and these treatments are therefore limited to heat-tolerant produce.

Brushing and high-pressure washing is also a successful treatment to remove quarantine pests that sit on the surface of fruit and vegetables. This is now an approved quarantine treatment for removal of leafrollers and their egg rafts from the surface of produce and is now in commercial use.

Irradiation

The use of ionising radiation is increasingly becoming an approved application in the world trade of food and horticultural products. Irradiation is regarded as a mature technology and has been demonstrated over many years to be a safe, reliable procedure to treat quarantine pests in fruit and vegetables. Some form of food irradiation is allowed in 60 countries, but its approval is country and produce specific. Generic irradiation treatments have been approved by US Department of Agriculture – Animal and Plant Health Inspection Service (USDA–APHIS) at doses of 150 Gray (Gy) for tephritid fruit flies, and 400 Gy for all insects except pupal and adult lepidoptera. Further rulings by the International Plant Protection Convention have approved minimum doses for six fruit fly pests and 14 other plant insect pests regardless of the host produce at doses ranging from 60 to 300 Gy. A big advantage of irradiation is that the treatment is not temperature dependent so chilling-sensitive tropical fruit can be disinfested with ionising radiation.

The egg phase of the life cycle of insects is generally the most sensitive to irradiation followed in order by larval, pupal and adult stages. Most insects are sterilised at doses of 100 to

1000 Gy. Although some adult moths will survive 1000 Gy, their progeny are sterile. Low dose irradiation (<1000 Gy) has been accepted as a quarantine treatment by many countries as it has not been shown to have any consistent adverse effects on fruit or vegetable quality.

Irradiation at doses of 50–300 Gy have been shown to be an effective alternative to chemical treatments to inhibit sprouting in potatoes, onions, garlic and yams. This dose range has little negative effect on other aspects of potato and onion quality such as sugar levels, rates of decay and water loss, texture and flavour. Irradiation of potatoes and onions is currently more expensive than treatment with CIPC and maleic hydrazide, but it is residue free. In addition, doses from 25–750 Gy have been shown to delay ripening in avocados, bananas, and some cultivars of mango and papaya. Irradiation at higher doses of 1000–3000 Gy has been shown to delay mould growth in fruits such as strawberries.

Thus, the potential benefits of gamma, electron beam or X-ray radiation in the postharvest handling of fruit and vegetables include both insect and disease disinfestation, and retardation of aspects of produce development such as ripening and sprouting (Table 11.6). While these potential benefits have been recognised for more than 50 years, the adoption of the technology has been slow, due mainly to regulatory authorities and public perceptions and acceptance of irradiation. However this is changing due to the commercialisation of non-nuclear sources of irradiation, such as X-rays. In addition, many countries now accept this disinfestation treatment against quarantine pests. This may further be enhanced with the introduction of tighter restrictions on disinfestation by chemicals and the demonstration of the benefits of irradiation.

Table 11.6 Effects of irradiation dose on selected fresh produce

	Beneficial effect (dose Gy)	Damage dose (Gy)
Fruits		In general injury (>1000)
Preclimacteric fruits	Delay ripening (<1000)	
Papaya (30% yellow)	Delay ripening (250)	
Mango	Delay ripening (<1000)	Scald and softening (>1500)
Banana	Extend shelf life (150–300)	Skin browning (>500)
Nonclimacteric fruits		
Strawberry	Reduced mould growth (1500–2000)	
Citrus	Maintain colour and firmness (400)	Peel pitting – cultivar dependent (150–600)
Blueberry	Improve quality (<750)	Softening and poor flavour (>1000)
Vegetables	Microbiological control (1000–3000)	
Fresh-cut celery	Extend shelf life and eliminate *E. coli* and *Listeria* (1000)	
Fresh-cut carrot	Control fungi and bacteria (2000)	
Tubers Potato, yam, garlic, sweet potato, ginger	Inhibition of sprouting (50–150)	

SOURCE Adapted from M. Wall (2008) 'Quality of postharvest horticultural crops after irradiation treatment', *Stewart Postharvest Review* 2:1.

12
Marketing and the consumer

There has been a continual shift over the years in the marketing of fruit and vegetables from a traditional industry supply-side dominance to meeting consumer demand. The increasing focus on the consumer has been driven by a range of factors, including greater competition in the market as a consequence of better postharvest technology. Developed postharvest technologies have extended the market season for many local commodities and allowed the transport of produce to more distant international markets, and many seasonal commodities are now available over the whole year. Another factor is the growing importance of fruit and vegetables as a profitable market segment within supermarkets which, when coupled with large specialist fruit and vegetable retailers, has changed the competitive landscape. This has often been to the economic detriment of producers, who need to meet the increasing regulation and quality requirements of the retailers with no increase in the wholesale price. The changing retail landscape has benefited consumers, as successful retailers are attuned to consumer attitudes and can set purchase standards to match consumer preference on produce quality.

The rise of the information age with the internet has had a profound impact on consumer access to information, and the growth of social media has further facilitated the sharing of this information to shape opinion and community attitudes. This influence has shaped perceptions of desirable and undesirable traits of fruit and vegetable quality. For example, perceptions of new health attributes such as antioxidants can elevate demand for certain produce. In addition, the rise of environmental awareness has given support to new concepts such as food miles, to induce consumers to purchase local produce (see later in this chapter). A positive outcome from information sharing has been its use by public health agencies to promote increased consumption of fruit and vegetables. However, the volume and heterogeneity of information and opinions is not always conducive to the formation of scientifically sound attitudes. While some consumer perceptions on desirable attributes of fruit and vegetables have a sound scientific foundation, others are more contentious and some are merely temporary fads. However, the consumer is king and fruit and vegetables that reflect current consumer preferences become a profitable market segment for the retailer and also for nimble growers who can adapt their growing systems.

While the primary focus of postharvest technology research still remains focused on maintenance of traditional quality attributes while extending storage life to enhance market opportunities for producers, the manner in which produce is handled and presented has changed. Consumer awareness has also raised safety, ethical and logistical questions that are altering notions of what constitutes an acceptable postharvest practice and what is expected from participants in the postharvest handling chain. This chapter will address a few of these issues as they relate to consumer trends in convenience marketing, environmental and safety considerations and organic produce.

Consumer influences on marketing

Fresh-cut produce

Fruit and vegetables which have had the inedible parts removed and the edible portion broken into smaller bite-size segments but retain all the properties of the fresh commodity are known as 'minimally processed', 'lightly processed' or 'fresh-cut' produce (Plate 13). Consumers have shown a strong desire for the convenience such products offer and are prepared to pay a premium price. This has resulted in phenomenal growth in the market segment. For example, retail sales of fresh-cut produce in the USA in 2012–13 were estimated at US$11 billion, and accounted for 16% of total retail sales of fruit and vegetables by value and 20% by weight. The dominant product was packaged salads (about 60% of total retail value), with other vegetables accounting for about 30% and fruits the remaining 10%. The five most traded fruit and vegetable categories (excluding packaged salads) in the USA are presented in Table 12.1. However, sales to the food service industry were greater, at US$16 billion, and reflect the value of convenience and quality consistency to professional food preparers.

The preparation of the market-dominant minimally processed iceberg and fancy lettuce salads in many countries involves a highly scheduled production operation that can involve early morning harvest, immediate fast cooling by vacuum or hydrocooling, trimming to remove damaged or unwanted parts, washing with potable water to remove farm and surface grit, disinfecting with an effective sanitiser, de-watering often by centrifugation, mixing the range of produce together, packaging under vacuum into sealed retail packs which may be

Table 12.1 Market share of fresh-cut fruit and vegetables in the USA in 2013

		Market share (% of total)	
Category	**Item**	**by value**	**by weight**
Fruits	Mixed fruit	33	21
	Apple	21	33
	Pineapple	16	16
	Watermelon	13	13
	Cantaloupe	5	5
Vegetables	Carrot	47	
(excl. salads)	Mixed vegetables	19	
	Green bean	7	
	Broccoli	4	
	Snap/snow peas	3	

SOURCE Adapted from Produce Marketing Association (PMA) (2014). Fresh-Cut Fruit and Vegetables, Market & Consumer Information ◂www.pma.com/~/media/pma-files/research-and-development/us-fresh-cut-f_v-markets-2014.pptx?la=en▸.

gas flushed with a modified atmosphere, and maintenance of a cool chain (e.g. 5°C) throughout distribution including during retailing from low temperature display cabinets. Figure 12.1 shows a supermarket refrigerated display cabinet with a wide array of packaged lettuce and salad mixtures.

While fresh-cut produce add value to a commodity, they come with a range of quality and safety issues. Many of these quality related issues derive from the removal of the protective outer layers of fruit during preparation that expose the underlying cells to the atmosphere and inflict damage on many cells. An overarching issue with fresh-cut produce is the increased

Figure 12.1 Refrigerated display of pre-packed lettuce

metabolic activity that is a consequence of tissues attempting to repair cellular damage. The increased metabolic activity is invariably observed by an increase in respiration, with the overall effect being an enhanced rate of senescence which reduces shelf life of the produce through enhanced loss of texture, flavour and nutrients. The use of modified atmospheres combined with low temperature is a common way of reducing metabolic activity.

A major challenge in fresh-cut produce is to prevent browning on the cut surface due to enzymic oxidation of polyphenols and the subsequent polymerisation of reaction products to brown pigments. The exposure of previously internal tissues to the atmosphere and damage to adjacent cells allows mixing of polyphenol substrates and phenolase enzymes that were previously in different cellular compartments. Browning can be inhibited by a range of techniques such as the use of chemicals that act as antioxidants (e.g. ascorbic acid, or acidulants such as citric acid) which create an unfavourable pH environment for reactions to occur. Edible coatings that reduce the exposure of outer cells to the atmosphere are also used. Calcium ascorbate dips have been found to be very effective in inhibiting browning on minimally processed apple slices and is now widely used in many countries.

An added significant potential hazard is contamination of fresh-cut produce with pathogenic bacteria. Contamination can occur in the field, during preparation and storage, and in the marketing chain which includes domestic handling. The release of cellular fluids from cells damaged during produce preparation provides a favourable nutrient medium for human pathogens to grow. It is imperative that good hygiene of premises and by workers be practised to limit contamination in the first instance, and this goes hand in hand with HACCP and cool chain management to minimise subsequent growth of toxic microorganisms. Surveys of health incidents related to fresh-cut produce have found *Salmonella* spp. to be the most common pathogen, with lettuces and cantaloupe (rock melon) the most reported commodities. The most common cause of contamination was attributed to poor quality water in postharvest operations and preharvest faecal contamination by wildlife. It is necessary that all fresh-cut operations have a strict HACCP QA management strategy that, among other things, prevents contact of produce with animal manures, ensures the packinghouse is cleaned regularly, and ensures all materials used including wash water are not contaminated and that workers always wash their hands before returning to the work site.

'Ripe and ready to eat' controlled ripening programs

Changing consumer habits to more frequent purchases of smaller quantities of fruit and vegetables to cater for smaller households has created a demand for 'Ripe and Ready to Eat' fruit, where consumers want to eat fruit soon after purchase and not wait for an unknown time before the fruit is ready to consume. This requires the supply chain to balance their preference to transport mature but unripe produce as they are less susceptible to transport and mechanical damage, with the need to place ripe fruit into retail outlets for the consumer. This scenario has been mastered by the banana industry, where unripe mature fruit are transported and then controlled ripening with ethylene is undertaken at wholesale markets to allow delivery of uniformly ripe fruit to retailers (see Chapter 11). The system works so well for bananas because of their high sensitivity to ethylene, where fruit with a wide range of maturity ripen at the same time.

The challenge for other fruits is to be able to measure maturity with some certainty and/or to have a ripening schedule that results in all fruit ripening uniformly at a predictable time or that can be easily sorted at the wholesale level to allow staggered marketing. Such systems have been developed for high-value produce such as mangoes, papayas and avocados. The successful management of such systems requires a high degree of technical knowledge, coordination with other market players, operational flexibility, reliable modern handling facilities and logistics and good marketing, all of which tends to favour large, diversified companies.

There is considerable interest in establishing a 'Ripe and Ready to Eat' protocol for dessert cultivars of peaches, nectarines and some Japanese-type plums that have a relatively firm texture when ripe. These fruits are usually harvested at a maturity stage several days in advance of an eating ripe stage to minimise bruising during grading and packing. Packed fruits are ripened to within about one day of eating ripe at 20°C and high RH using forced air circulation. Once the desired stage of ripeness is reached, based on firmness measurements (e.g. 4 kg flesh firmness), the fruit must be rapidly cooled by forced air to less than 2°C and maintained at low temperature until they are rapidly transported and placed on retail display.

Environmental and safety issues

Packaging

Packaging for horticulture produce has considerable environmental implications because of the large quantities of materials involved and their eventual disposal. Wooden packaging is biodegradable as is fibreboard and paper packaging, which are also recyclable. However, these materials are forest products and management of forest resources is a strong consumer issue.

Figure 12.2 **Returnable collapsible plastic boxes used for 'retail-ready' display of produce**

The recycling of fibreboard has been a significant benefit for the packaging industry, but re-capture of boxes back into recycling can be poor. The use of returnable plastic crates that are washed and reused many times (Figure 12.2) has been widely adopted in many closed markets. They can be used from the farm to the retail display in the store (Plate 14). Their introduction has greatly reduced the volume of one-way packaging. Plastic films that are extensively used for packaging can be recycled, although stringent recycling practices are not common. Expanded polystyrene is not biodegradable and can only be recycled using expensive capital infrastructure into high-density material.

Most plastics currently used in packaging are manufactured from petroleum sources and concerns about environmental impacts and sustainability of their production, disposal and recycling are leading to the use of alternatives such as bio-based polymers. The first generation of bio-based plastic polymers are derived from agricultural feedstocks such as corn, potatoes, and other carbohydrate materials and can be composed of starch, cellulose or protein. Although bio-based polymers currently share less than 1% of the total market, interest in their development and application is growing. In recent years the focus has shifted from food-based resources to bioengineered polymers produced by bacterial fermentation of non-food renewable resources such as lignocellulosic biomass, fatty acids and organic wastes.

However, sustainable packaging is the use of packaging which results in improved sustainability – it is not just focused on recycling. This has evolved notions of life cycle inventory and life cycle assessment to assess the total environmental impact and ecological footprint of packaging materials. This approach looks at the whole of the supply chain: from basic function, to marketing, through to end of useful life and rebirth. While the use of bioplastics, recycling and biodegradable plastics improve the sustainability of packaging, some studies have concluded that none of the bio-based plastics currently in commercial use or under development are fully sustainable.

Fruit stickers

Fruit stickers were developed to allow ready identification of produce at the retail checkout. Their use is now ubiquitous, but in the minds of many consumers they are wasteful, unnecessary and even annoying. The stickers and the backing glue are required to be made from edible materials, but many consumers are wary of their accidental consumption on health and taste perceptions. For many food service operators, removing the stickers is a costly, time-consuming exercise. Some new technologies which may overcome these concerns are the use of a laser to imprint a barcode into the skin of fruit such as citrus, and water-soluble stickers that dissolve if the fruit is washed.

Chemical residues

The use of chemical fungicides and pesticides has undoubtedly increased the volume of fruit and vegetables marketed around the world, but consumers are increasingly concerned about potential health hazards from residues in produce as well as unintended environmental impacts. The earliest example that triggered environmental concern was DDT (dichlorodiphenyl-trichloroethane). This is a highly effective insecticide but its harm to non-target species and persistence in the environment led to it being banned in 1972 by the US Environmental Protection Agency. But residues are still being detected in the soil in many countries – more than 40 years later.

The focus turned to develop agricultural chemicals that are more target specific, which have a limited life in the environment and are non-toxic to humans. While stringent maximum residue limits (MRLs) are now established for all chemicals during the approval process, some consumers remain wary of any synthetic chemical being used with foods. As discussed in Chapter 9, there is renewed interest in using natural compounds derived from plants, or biological controls, but they still need to be rigorously evaluated as they may be toxic to humans. Alternative methods of pest and disease control include physical treatments or compounds with GRAS status.

Labelling issues

Consumer awareness has led to processed food products in most countries being required to have substantial information on product labels. This can include listing all the ingredients, the country of origin of the major food constituents, and nutritional information on certain nutrients but limiting health claims for the food. Such labelling is intended to assist consumers to make informed choices.

Fresh fruit and vegetables have generally not been required to carry such information as it is deemed unnecessary and even impractical to label a natural raw food, especially if it is not packaged at the point of sale. Once it is packaged, such as with fresh-cuts, then some product information is required, but this requirement varies between countries. In addition, there are often mandated requirements for the store label that advertises the produce and its price. This can also include country of origin labelling and if it has been genetically modified or irradiated.

Energy sustainability

There is growing concern by communities and governments about the need to limit the emission of greenhouse gases; indeed, countries attending the UN Framework Convention on Climate Change in 2015 agreed to limit global warming to less than 2°C. The increasing cost of energy is often an incentive for households and industry to reduce energy use. Thus, for industry there is a dual incentive of an economic benefit and being seen as responsible citizens by reducing energy consumption.

Refrigeration is a major user of energy in the postharvest supply chain and many simple steps, such as improved cool room insulation, can be taken to increase the efficiency of existing operations. Further savings can come through better produce management such as using the actual temperature required to meet market life requirements. For example, it is not necessary to cool and use CA storage for freshly harvested apples that will soon go to market.

For longer term storage, it would seem logical to examine the potential of using cheaper technologies such as ethylene management before considering the larger change of moving to alternative energy sources such as solar panels. Energy savings within supply chains could also be made during the transport of produce through an audit of the transport chain that addressed many of the issues mentioned above.

Supermarkets and specialist fruit and vegetable retailers use refrigerated cabinets as well as unrefrigerated display areas for fresh produce. But inspection of outlets often indicates poor management or a lack of understanding at store level of which produce requires refrigeration and which could be held at room temperature – an audit of practices and produce throughput coupled with better staff training could reduce the area needed for refrigerated display.

Many manufactured electrical household products now carry an energy rating based on a star system to indicate their energy consumption relative to a set of mandated standards. It could be seen as desirable that a similar energy rating could be developed for individual consignments of fruit and vegetables. One such attempt and an energy rating for foods in general is the concept of food miles, which was developed in the United Kingdom in the 1990s and measures the distance a food is transported from the farm gate to the consumer – it makes the assumption that the higher the food miles for a product, the greater the greenhouse gas emissions. Use of this concept was intended to allow consumers to purchase produce that had fewer food miles. However, transport is only a part of the energy used to produce food and thus food miles are poorly correlated with the actual environmental impact of food production. Audits of energy usage over the whole production chain have shown much greater energy usage occurs in the production phase. Even then, transport only accounts for a small proportion of the post-farm gate energy usage. A more useful measure would reflect the energy usage across the total life cycle of a produce.

Organic fruit and vegetables

Traditional farming without the use of chemicals has been practised for millennia. However, the practice of organic farming was specifically developed in the 1930s as a method of retaining soil quality and biological diversity through the scientific use of traditional, more natural methods of farming. The principles of organic farming aim to have a largely self-sufficient farm that relies on techniques such as crop rotation, composting, animal manures and biological pest control. It excludes the use of synthetic pesticides and fertilisers, genetically modified organisms and nanomaterials, but allows the use of natural plant extracts as pesticides and a range of acceptable mineral formulations. The principles of the organic movement can be considered as much a philosophy as just a method of farming.

The popularity of organic foods among consumers has accelerated since the 1990s, largely as a community response to concerns about chemical residues and environmental changes caused by 'modern' farming practices. Organic foods generally attract a price premium and the potential for misrepresentation in the marketplace has led many governments to regulate the practices that must be followed before foods can be marketed as 'organic' – in 2007 over 60 countries had established regulations for organic farming. While regulations may differ slightly between countries, they are based on standards set by the International Federation of Organic Agriculture Movements (IFOAM). The regulations also stipulate a strict ongoing record-keeping regime for all operations and an independent inspection protocol to gain and maintain accreditation to market produce as organic.

The world market for organic food was estimated at about US$63 billion in 2012. This was produced from 37 million hectares (about 90 million acres), which represented about 1% of total world farmland. The country with the most organic land was Australia (12 million hectares), with grazing free-range cattle the principal activity. However, fresh fruit and vegetables are the top-selling category of organically grown food and in the USA account for nearly 50% of the organic market. In Australia, fresh fruit and vegetables account for about 60% of consumer purchases of organic foods, with the top fruit sales being for apples, citrus and olives, while the top selling vegetables are carrots, potatoes, broccoli and pumpkin. There remains considerable debate about whether organically produced foods have different levels of nutrients and anti-nutrients compared to conventionally produced food. The variable nature of food production, handling and cultivars makes it difficult to generalise results and there is insufficient evidence to support claims that organic food is safer, healthier or tastier than conventional food.

Organic postharvest management

Ensuring the correct storage temperature and proper postharvest handling are the two fundamental keys to manage both organic and conventionally grown horticultural crops. However, the postharvest storage and handling of organic produce presents some specific challenges, particularly in decay control. There is a range of approved physical, chemical and biological postharvest treatments to maintain quality and minimise losses of organic produce, although the approved treatments vary between countries. Table 12.2 presents some typical approved postharvest treatments and materials.

Table 12.2 Typical approved treatments for postharvest use on organic fruit and vegetables

Carbon dioxide (i.e. modified atmospheres)
Calcium chloride
Detergents (natural and biodegradable)
Ethylene
Fumigants derived from natural sources
Waxes from natural sources (e.g. carnauba wax)
Volatiles (e.g. acetaldehyde)
Citric and malic acids
Sanitisers/cleaning agents
Chlorine (at prescribed levels)
Ozone
Hydrogen peroxide (food grade)
Acetic and related acids
Ethanol
Peracetic acids
Natural soaps

An example of the difference in organic treatment approvals between countries is the use of ethylene. While it is produced naturally by all horticultural produce, its application for artificial ripening of organic produce is often restricted to certain produce. For example, the European Union and Japan only allow its use for banana ripening. Conversely, the removal of ethylene with potassium permanganate is permitted provided there is strict separation of the oxidant from produce.

Physical treatments such as the use of heat treatments, curing and controlled atmosphere storage are acceptable and have been shown to minimise losses of organic produce. Natural compounds obtained from plants, animals or microorganisms, including some volatiles, essential oils, phenolic compounds, plant extracts, peptides, alkaloids, lectins and chitosan, are being assessed for organic suitability.

Food safety is the most important aspect of any production system, with sanitation an integral part of every postharvest system. This is particularly important in organic production where organic loads on produce can be high since animal manure is a feature of organic farming. The presence of disease-causing organisms such as *E. coli* 0157:H7, *Salmonella*, *Shigella*, *Listeria*, *Cryptosporidium* and *Cyclospora* have been associated with organic fruit and vegetables. Sanitation of harvested produce and keeping all equipment free of human and plant pathogens is critical. However, the water used for washing must not contain any dissolved prohibited substances which could void organic certification. Chlorine is allowed to disinfect water and sodium hypochlorite is also commonly used, but the residue in downstream operations must be below the allowable level for potable water (often 4–10 mg/L Na). Acetic acid and ethanol are approved sanitisers, but they must be obtained from an organic source.

Decay control also presents particular problems for organic produce because synthetic pesticides are not used. Organic produce needs to have an integrated approach to disease management. This requires managing all preharvest, harvest, transport, storage and marketing factors that affect decay and quality. The control of postharvest pathogens can be improved with reduced inoculum and infection levels in the field, effective fruit and packinghouse sanitation to reduce atmospheric and superficial inoculum levels, appropriate practices during handling and storage to maintain fruit resistance to infection; and, if applicable, suitable organic treatments can be adopted to minimise decay. Alternative decay control methods can be physical, chemical or biological, as discussed in Chapter 9.

An important component of organic produce is the strict requirement that all practices must be fully documented and acceptable methods used on organic produce must be listed by the relevant national organic codes. Mixed load shipping with conventional produce is acceptable but presents some management issues. Organic produce must be held in a package that is clearly labelled and no physical contact must be made with conventional produce. Where organic produce is shipped in bulk, the containing vessel or vehicle must not contain residues of any non-approved material. While organic regulations allow some minor exceptions to additives and treatments being fully natural, the overriding consideration is that all postharvest operations retain the 'organic' integrity of produce. The ongoing monitoring of organic enterprises by accrediting agencies is intended to give confidence to consumers they are purchasing true organic produce.

Glossary of botanical names

Common and botanical names of selected fruits and vegetables

Common name	Botanical name
Apple	*Malus x domestica* Borkh
Apricot	*Prunus armeniaca* L.
Asian pear	*Pyrus pyrifolia* Nakai and *P. bretschneideri* Rehder
Asparagus	*Asparagus officinalis* L.
Avocado	*Persea americana* Mill.
Banana	*Musa L* sp. Cavendish cultivars *M. acuminata* Colla
Beans, broad	*Vicia faba* L.
string	*Phaseolus vulgaris* L.
mung	*Phaseolus aureus* Roxb.
Beetroot	*Beta vulgaris* L.
Blueberry	*Vaccinium* sp.
Broccoli	*Brassica oleracea* L. (Italica group)
Brussels sprout	*Brassica oleracea* L. (Gemmifera group)
Cabbage	*Brassica oleracea* L. (Capitata group)
Capsicum (sweet pepper)	*Capsicum annuum* L.
Carambola	*Averrhoa carambola* L.
Carrot	*Daucus carota* L.
Cassava (manioc, tapioca)	*Mannihot esculenta* Crantz
Cauliflower	*Brassica oleracea* L. (Botrytis group)
Celery	*Apium graveolens* L.
Cherimoya	*Annona cherimola* Mill.
Cherry, sweet	*Prunus avium* L.
sour	*Prunus cerasus* L.

Common name	**Botanical name**
Chilli	*Capsicum annuum* L.
Choko	*Sechium edule* (Jacq.) Sw.
Corn (maize), sweet	*Zea mays* L.
Cucumber	*Cucumis sativus* L.
Eggplant (aubergine, brinjal)	*Solanum melongena* L.
Feijoa	*Feijoa sellowiana* Berg.
Fig	*Ficus carica* L.
Garlic	*Allium sativum* L
Ginger	*Zingiber officinale* Rascoe
Globe artichoke	*Cynara scolymus* L.
Grape	*Vitis vinifera* L.
Grapefruit	*Citrus paradisi* Macfad.
Guava	*Psidium guajava* L.
Jackfruit	*Artocarpus heterophyllus* (Lam.) L.
Jerusalem artichoke	*Helianthus tuberosus* L.
Kiwifruit	*Actinidia deliciosa* (A. Chev.) C.F. Liang et A.R. Ferguson
Leek	*Allium ampeloprasum* L.
Lemon	*Citrus limon* (L.) Burm. f.
Lettuce	*Lactuca sativa* L.
Lime	*Citrus aurantifolia* (Christm.) Swingle
Litchi	*Litchi chinensis* Sonn.
Loquat	*Eriobotrya japonica* Lindl.
Mandarin	*Citrus reticulata* Blanco
Mango	*Mangifera indica* L.
Mangosteen	*Garcinia mangostana* L.
Muskmelon (cantaloupe, honey dew)	*Cucumis melo* L.
Nectarine	*Prunus persica* (L.) Batsch.
Okra	*Hibiscus esculentus* L.
Onion	*Allium cepa* L.
Orange	*Citrus sinensis* (L.) Osbeck
Papaya	*Carica papaya* L.

Common name	**Botanical name**
Parsley	*Petroselinum crispum* (Mill.) Nym.
Parsnip	*Pastinaca sativa* L.
Passionfruit	*Passiflora edulis* Sims
Pea	*Pisum sativum* L.
Peach	*Prunus persica* (L.) Batsch.
Pear	*Pyrus communis* L.
Pepino	*Solanum muricatum* Ait.
Peppers, green and red	*Capsicum annuum* L.
Persimmon	*Diospyros kaki* L.f.
Pineapple	*Ananas comosus* (L.) Merr.
Plum	*Prunus domestica* L.
Pomegranate	*Punica granatum* L.
Potato	*Solanum tuberosum* L.
Pumpkin	*Cucurbita pepo* L.
Radish	*Raphanus sativa* L.
Rambutan	*Nephelium lappaceum* L. var. *esculentum* Nees
Rhubarb	*Rheum* sp.
Satsuma mandarin	*Citrus unshu* Mari
Spinach, European	*Spinacia oleracea* L.
Squash	*Cucurbita maxima* Duch.
Strawberry	*Fragaria x ananassa* Duch.
Swede turnip	*Brassica napus* L. (Napobrassica group)
Sweet potato	*Ipomea batatas* (L.) Lam.
Tamarillo (tree tomato)	*Cyphomandra betacea* (Cav.) Sendt.
Taro	*Colocasia esculenta* (L.) Schott
Tomato	*Lycopersicon esculentum* Mill.
Turnip	*Brassica campestris* L. (Rapifera group)
Watermelon	*Citrullus lanatus* (Thunb.) Mansf.
Yam	*Dioscorea batatas* Deene
Zucchini (courgette)	*Cucurbita pepo* L. var. *cylindrica*

Index

Index

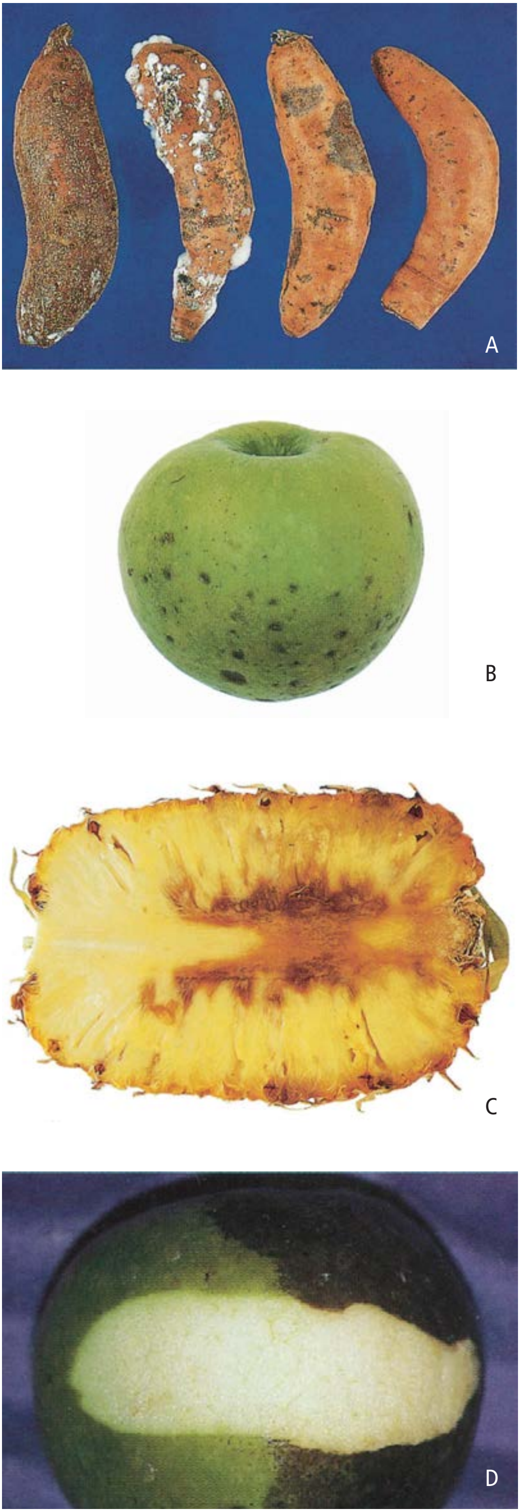


Plate 1 Illustrations of non-pathogenic diseases: (A) occurrence of chilling injury of sweet potato following seven weeks storage at (left to right) 0°C, 5°C, 10°C and 15°C; (B) bitter pit of apple; (C) black heart of pineapple (in Australia this condition is usually caused by preharvest chilling); (D) superficial scald of Granny Smith apple stored at 0°C showing that browning does not extend below the skin.

SOURCE Plates A–C: courtesy of B.B. Beattie, formerly NSW Department of Agriculture.

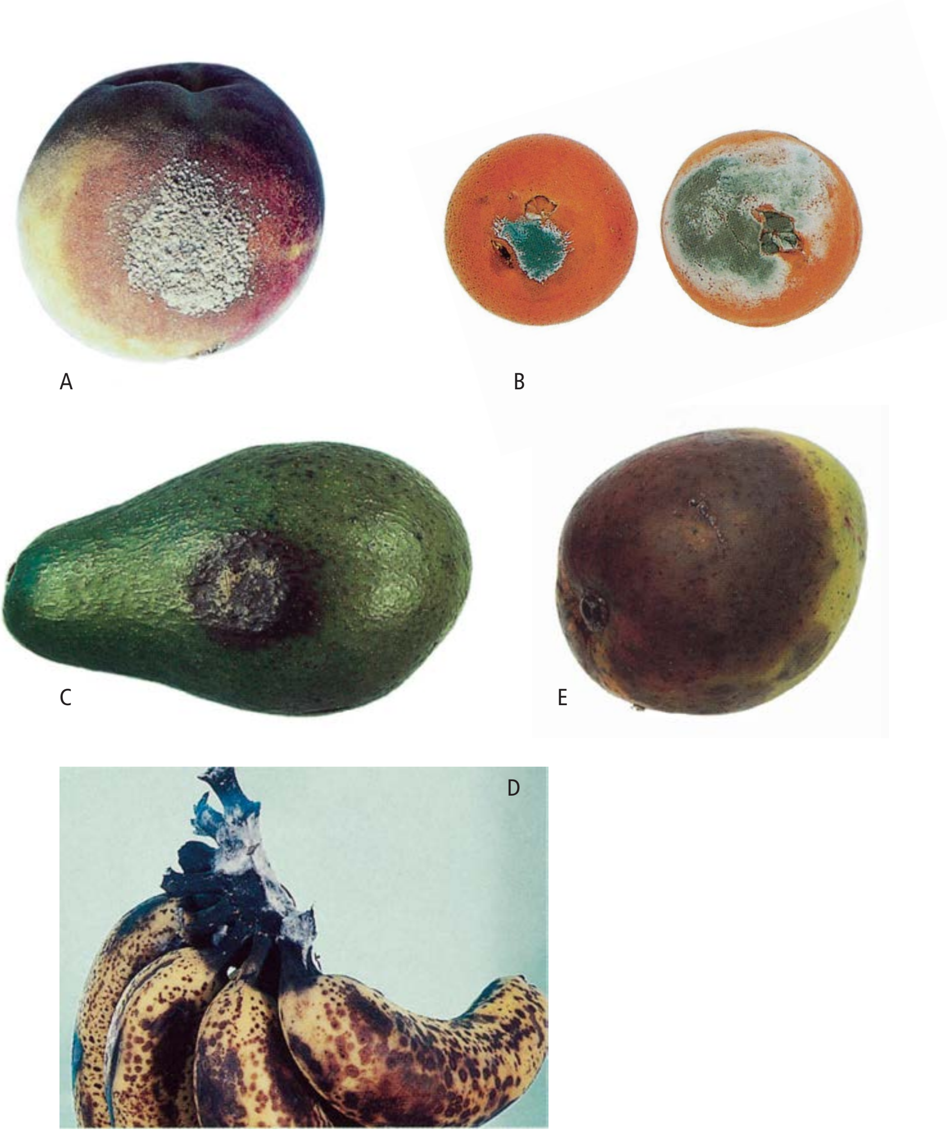


Plate 2 Illustrations of pathological diseases: (A) brown rot (*Monilia fruticola*) of peach; (B) blue mould (*Penicillium italicum*) (left) and green mould (*P. digitatum*) (right) of oranges; (C) anthracnose (*Colletotrichum gloeosporiodes*) of avocado; (D) crown rot of bananas caused by several species of fungi; (E) stem-end rot of mango (*Dothiorella dominicana* is the most common cause of this rot in Australia).

SOURCE Courtesy of B.B. Beattie, formerly NSW Department of Agriculture.

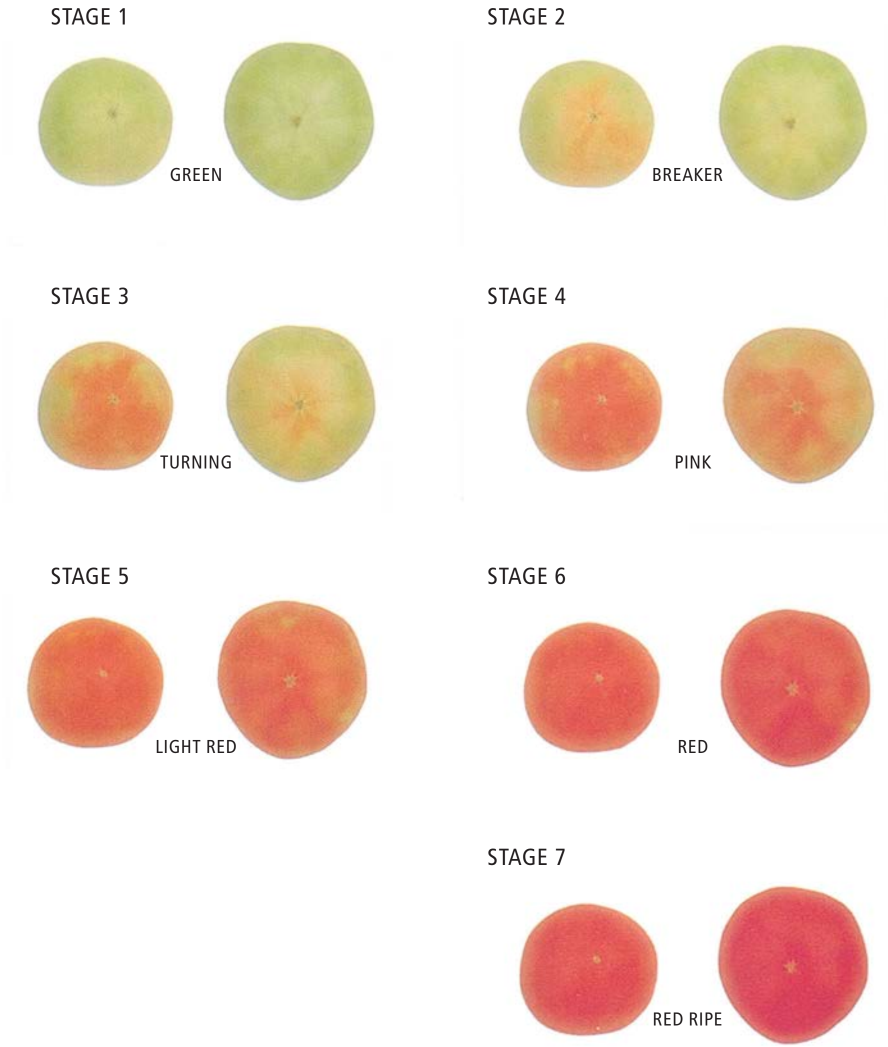


Plate 3 Tomato colour chart. Individual fruit ripened at 20°C were photographed daily. Stage 2, day 2 of the climacteric rise in respiration and ethylene production, coincides with colour stage 2 (breaker). Stage 6: tomatoes reach an overall red stage four days from the breaker stage. At least two more days of ripening are required for the fruit to develop full flavour.

SOURCE W.B. McGlasson, B.B. Beattie and E.E. Kavanagh (1985) 'Tomato ripening guide', *Agfact* H8.4.5, NSW Department of Agriculture, Sydney.

Plate 4 Apple starch iodine scale used to assess the apple fruit maturity

SOURCE Don Edwards, University of California, Davis, CA.

4 =

All area within coreline white, ½ area of cortex white, remainder blue.

5 =

All area within coreline white, ¾ of cortex area white.

6 =

All surface white.

The reaction of iodine solution on any starch present in the apple turns the cut surface blue. The greater the starch content the greater the area of blue color.

In the starch-iodine index numbering system 0 represents immature, and 6 fully ripe fruit. The following descriptions represent the upper limit of each index point.

When the average of a thirty fruit sample is 2.5 or higher, it meets the minimum maturity requirements. The samples should represent the variation of sizes in the orchard.

The Chart should be used as follows:

1. Use the descriptive terms to determine the numerical value of each sample apple.
2. Compare the sample to the pictures to make sure you are interpreting the chart correctly.
3. Samples difficult to categorize will be assigned the higher value.
4. Each apple is assigned a whole number not a decimal (1.0, 2.0, 3.0, not 1.2, 2.4, 2.7).
5. The 2.5 standard is a mathematical average of the samples (the sum of all scores divided by thirty).

CROSS SECTION OF AN APPLE

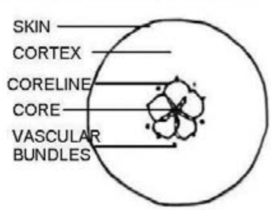


Plate 5 Brushing and washing melons to remove dirt and debris

SOURCE Dr S.P. Singh, NSW Department of Primary Industries.

Plate 6 Transfer of apples through the packing line in sanitised water (A) and on rollers (B)

Plate 7 Citrus packing line (A) and blueberry packing (B)

SOURCE Dr J.B. Golding, NSW Department of Primary Industries, in CABI Horticulture Compendium.

Plate 8 Cherry sorting and grading (A and B) and onion packing (C and D – see following page)


C


D

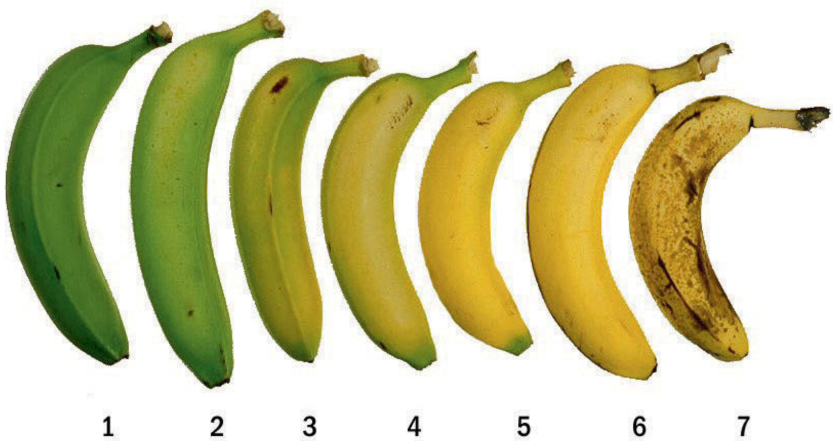


Plate 9 Banana ripening scale. A seven-point ripening scale is often used to quantify the stage of ripeness in banana ripening.

SOURCE Don Edwards, University of California, Davis, CA.

Plate 10 Fibreboard bins of pumpkins (A), woven bags of melons (B), netted bags of oranges (C). Note all on pallets for transportation.

Plate 11 Cut-away view of apple box

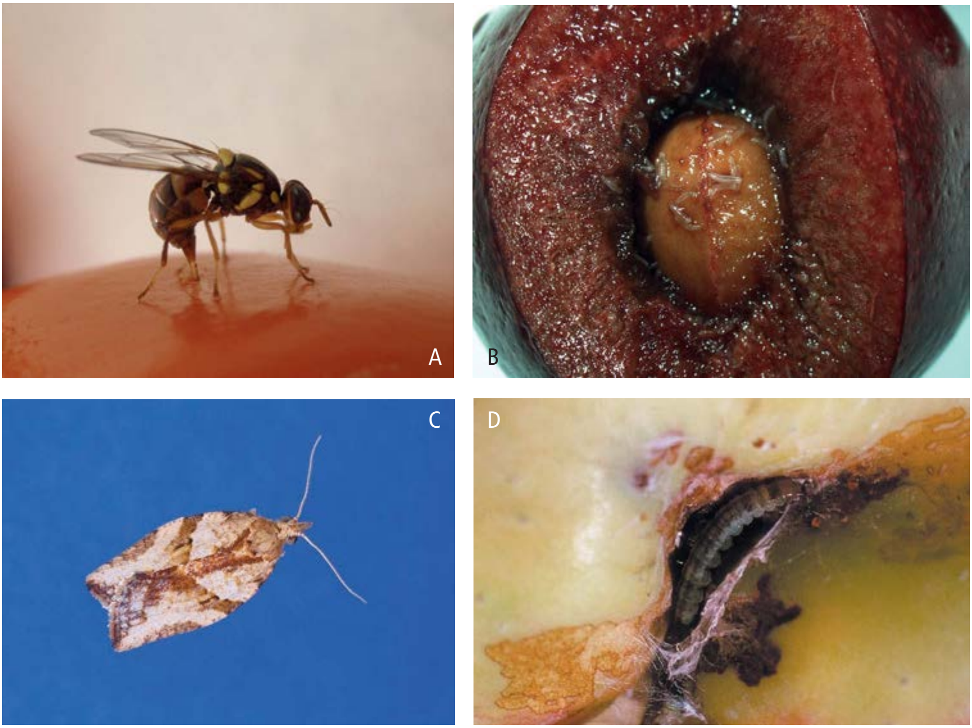


Plate 12 Adult Queensland fruit fly (*Bactrocera tryoni*) on a persimmon (A); Queensland fruit fly larvae in a cherry (B); adult light brown apple moth (*Epiphyas postvittana*) (C) and its pupating larva, showing typical protective webbing (D)

SOURCE Plates C & D: courtesy of NSW Department of Primary Industries.

Plate 13 Minimally processed fruit and vegetables: (A) ‘minimally processed’ tropical fruit; (B) selection of ‘minimally processed’ fruit in a supermarket

SOURCE Dr J.B. Golding, NSW Department of Primary Industries, in CABI Horticulture Compendium.

Plate 14 Rigid plastic apple crates (A) used in transport and (B) on retail display in a supermarket

SOURCE Plate B: Courtesy of Woolworths Ltd.

POSTHARVEST

An Introduction to the Physiology and Handling of Fruit and Vegetables

6TH EDITION

RON WILLS AND JOHN GOLDING

'I can never remember a time when this book was not on my shelf! It serves as a wonderful resource for the practitioner, whether in industry or academia, as well as for students, providing great core information about postharvest science. I am therefore delighted to see this complete revision and 6th edition. Several key updates make this book an even better resource for anyone wanting a thorough understanding of postharvest basics and application.'

Christopher Watkins, Professor of Postharvest Science, Cornell University

Completely updated, this broad-based introductory level textbook covers the key concepts and practical technologies to slow the deterioration of harvested produce, including handling, packaging, transport, temperature management and the control of pests and diseases. The book retains its high quality colour section and the content has been revised to reflect up-to-date information on the key issues of effective postharvest handling.

New to the sixth edition:

- Discussion of issues important to consumers and the impact of trends in convenience marketing on the quality of fresh-cut produce
- Coverage of sustainability in terms of both energy used by technologies and non-synthetic disease and pest control systems
- Greater consideration given to preharvest factors that influence quality
- Additional information about the health benefits of plant antioxidant properties and a discussion of 'superfoods'

This new edition is an invaluable resource for students of horticulture, plant physiology and food science, and industry personnel involved with the transportation, warehousing, marketing and retailing of fresh produce.

Space for bar code with ISBN included