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Sustainable Insect Pest Management

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Foreword

The digital age has its preferences. The reading time has been encroached upon by a watching time. The access to information is easy and a plenty where Wikipedia has emerged as the most powerful encyclopedia ever. Yet, a book is a book! We wish to promote the habit of reading books. Finding books is not difficult or expensive (www.pdfdrive.com) but a local context and indigenous experiences could be missing.

The University of Agriculture, Faisalabad (UAF) has achieved global rankings of its flagship programs and acceptance as a leader in the field of agriculture and allied sciences. A competent faculty, the stimulating ecosystem and its learning environment have attracted increasing attention. Publication of books is an important KPI for any institution of higher learning. Hence, UAF has embarked upon an ambitious 'books project' to provide reference texts and to occupy our space as a knowledge powerhouse. It is intended that the UAF books shall be made available in both paper and electronic versions for a wider reach and affordability.

UAF offers more than 160 degree programs where agriculture remains our priority. There are about 20 institutions other than UAF who are also offering similar degree programs. Yet, there is no strong history of indigenously produced text/reference books that students and scholars could access. The last major effort dates back to the early 1990's when a USAID funded TIPAN project produced a few multiauthor text books. Those books are now obsoleted but still in demand because of lack of alternatives. The knowledge explosion simply demands that we undertake and expand the process anew.

Considering the significance of this project, I have personally overseen the entire process of short listing of the topics, assemblage of authors, review of contents and editorial work of 29 books being written in the first phase of this project. Each book has editor(s) who worked with a group of authors writing chapters of their choice and expertise. The draft texts were peer reviewed and language corrected as much as possible. There was a considerable consultation and revision undertaken before the final drafts were accepted for formatting and printing process.

This series of books cover a very broad range of subjects from theoretical physics and electronic image processing to hard core agricultural subjects and public policy. It is my considered opinion that the books produced here will find a wide acceptance across the country and overseas. That will serve a very important purpose of improving quality of teaching and learning. The reference texts will also be equally valued by the researchers and enthusiastic practitioners. Hopefully, this is a beginning of unleashing the knowledge potential of UAF which shall be continued. It is my dream to open a bookshop at UAF like the ones that we find in highly ranked universities across the globe.

Insect pests remain a major constraint to crop productivity, quality of produce and food safety. The climate change has affected the biology and behavior of indigenous and exotic pests. This book would bridge the knowledge gaps in sustainable pest management for optimal productivity and food safety. The text has all the elements of pest management needed for a good classroom level audience as well as for the farm managers fighting the pests in the real farm situations.

Before concluding, I wish to record my appreciation for my coworker Dr. Muhammad Farooq who worked skillfully and tirelessly towards achieving a daunting task. Equally important was the contribution of the authors and editors of this book. I also acknowledge the financial support for this project provided by the USDA endowment fund available to UAF.

Prof. Iqrar A. Khan (*Sitara-e-Imtiaz*)
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Preface

Improvement in quantity (yield) and quality of food, fiber and ornamental crops and substantial development in food-safety and food-security have been dependent on the progress and modernization in the pest management technologies that have been revolutionized in twenty first century. Agriculture has been revolutionized with the advent of green revolution in agriculture. But the demand for the quality food has been increased drastically especially in the developing countries is a huge concern. A gigantic gap exists between the amount of food produced and the demand for the increasing world particularly in the coming decades. This gap should be minimized by enhancing the agriculture productivity and improving the food security. The agriculture productivity and food-security can be improved by using innovative efficient crop production and protection technologies and ameliorating the important limiting factors in agriculture system. Insect pests are the major constraints for crop productivity that should be managed to ensure better production and food safety/security. But compiled and comprehensive knowledge of the globally recognized pest management technologies and sustainable pest management strategies/programs is not available in understandable language in the developing countries. This book would bridge this gap and contribute to food productivity, safety and security in developing countries especially Pakistan at large.

Changing climate has not only changed the biology, behavior and status of the dominant indigenous insect-pests but also resulted in successful invasion and establishment of exotic insect pest species. The ecological concept of pest management has entirely been changed in present scenario of climate change. This altering climate has driven transformation of pest demography, bionomics, ecology, biology, behavior, interactions and pest management concept. The improvements are needed either in existing pest management techniques or development of climate resilient crop production and protection technologies. Such changes also culminate on the exploration and development of new pest management approaches as well as their dissemination with comprehensive strategic instructions through electronic and print media. It is also indispensable for researchers, technology developers and end-users to have comprehensive information about the pest management knowledge, all-inclusive biological acquaintance about the target pest and wide-ranging acquaintance and understanding of the paramount principles of pest management for successful and sustainable implementation of single or multiple-attacking-system approach of any pest management program. This book highlights the information of various conventional and innovative pillars of an efficient, economical and ecofriendly sustainable pest management program.

The scientific discoveries in form of conventional and innovative pest management technologies had been made and exploited successfully in the past. Still new incredible and implausible discoveries in the field of insect pest management are being accomplished using modern molecular and biotechnological approaches in various parts of the world. Such discoveries have also expanded the concepts of insect pest management program. The detailed information on the concepts, potentials and present scenario of successful conventional and farfetched modern pest management technologies are available in litreature but in scatted form. It is imperative and imperious to collect and present comprehensive, well-illustrated, up-to-date, general and applied accounts and descriptions of such technologies in a simple, lucid, easily understandable language for research scholars, under- and post-graduate students and extension workers of developing countries. This book aims to achieve afore-mentioned paramount objective. I anticipate that this book will also serve as an indispensable and valuable reference material on sustainable management of economic insect pests and would be of paramount significance for the academia, research-communities, students, extension workers and other stakeholders involved and interested in the management of insect pests of economic crops in developing countries. This book is the result of recognized need and attempt to cover the pest management from multidisciplinary and multi-faceted components. It consists of ten chapters written on various aspects of sustainable insect pest management.

First chapter highlights the in-depth and exhaustive knowledge on concepts, classification, losses and control paradox of insect pests. The second chapter depicts detailed portrayal on the paramount principles of insect control. Third chapter of this book reviews the types and components of insect-plant interactions, concept of tritrophic relationship, mechanisms and genetic basis of host plant resistance to insects and potentials of utilizing insect-plant interactions in IPM with case-studies. Comprehensive reviewed information on the biology, host-plants, mode of damage and management of insect pests of economic crops, fruits and vegetables have been described in the chapter-4, 5 and 6 respectively. The Seventh chapter discusses on the biology, classifications and toxins of insect's pathogens (entomopathogens) and their potentials in integrated pest management program as biocontrol agents. The chapter 8 highlights the concepts, categories and potentials of biorational approaches based on insect's growth, development, cuticle, hormones and pheromones; as well as plant-, herbivore- and natural-enemy-produced allelochemicals in IPM. The 9th chapter emphasizes on the comprehensive description of the various biotechnological approaches and their potential utilization in pest management program of economic crops with special reference to genetically modified organisms (GMOs) and genetically modified crops (GMCs). The last (10th) chapter discusses the promise and perils of the development and implementation of IPM programs and presents case studies and future of IPM/ICM.

This book is the outcome of cohesive and consistent effort as well as contribution of various national and international research scholars and academia professionals who are focusing their research activities or have colossal experience on applied entomology. I hope that the current book will prove useful to all those in interested in promoting the cause of sustainable pest management in formal and informal applications in both developed and developing countries that can be able to achieve the sustainability in agricultural system and environmental protection for future generation. The auditors of this book pay a token of profound gratitude to the devotions of all the authors and co-authors for their extended perceptive contributions, regular assistance and dexterous cooperation during write-up and revision process of respective chapters as well as of this book at large. There is a

huge list of hidden contributors who either present their collective thinking and philosophies on IPM as pioneer or who have contributed the building blocks of modern agricultural and pest management science in the era of twenty-first century. Listing all such contributor in this book would run the risk of inadvertently omissions. The editors of this book, therefore, acknowledge and appreciate the contributions of such contributors in agricultural and pest management science.

It has been a time consuming, hectic and daunting task to prepare this book; but the encouragement, patience and editorial assistance of the convener of book-writing project (Dr. Muhammad Farooq) have made it possible within the stipulated time period. We do acknowledge the enthusiastic encouragement and motivation of Vice Chancellor, Prof. Dr. Iqrar Ahmed Khan (*Sitara-e-Imtiaz*) that inspired us to accomplish this task under his inspiring, captivating and blazing leadership at UAF. No doubt, the accomplishment of this book remains incomplete if the due assistance and guidelines of the publishing agency has not been with us. We anticipate and hope that this book would become a cutting-edge, trailblazing, pioneering and advanced reference book for under- and post-graduate students, teachers/academicians, research scholars and extension-workers. This humble effort would also substantiate itself as a beneficial and valuable source in promoting the use of sustainable management approaches nationally as well as internationally especially in other developing countries.

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Chapter 1

Insect Pest Management

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Abstract

The future of crop production is threatened by the incidence of insect pests. Emergence of pest resistance caused substantial crop losses globally and considered a hurdle for the accomplishment of productivity and poverty alleviation worldwide. Over-reliance on chemicals to control insect pests is associated with ecosystem contamination and additional hazardous health effects. It is now clear that shift approach for pest control is immediately required to elucidate the growing concerns associated with pesticides. Therefore, it is needed to design cropping systems without ecological disruptions and less dependent on synthetic pesticides. Integrated pest management emphasis is on anticipating pest problems followed by simultaneous integration of different approaches, the consistent monitoring of insect pests and their natural enemies and thresholds assessment for decision making. Pest outbreaks and consequently their dynamic and flexible management can only be achieved by restructuring, preventive and therapeutic measures in ways that enhance the crop productivity. In current chapter the focus will be about pest management strategies, the impacts of IPM and its potential contribution to the various crops.

Keywords: Insect pests, Crop losses, Pest control, Preventive, Therapeutic, IPM

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1.1. Introduction

1.1.1. Concepts of insect pests

Man has to compete with insect pests since the start of crop production around 10, 000 years ago for many of his fundamental needs. For this reason, battle lines were drawn right from pre-historic days. A skyrocket increase in the human population (ca. 80 million per annum) (United Nations 1996), changes in nutritional trends especially in the less developed countries towards the quality foodstuffs caused food availability problems. Additionally, decrease in the per-capita crop land availability, poor management and pest-associated losses are also the key repercussions for food safety. From the last few years, food production has been lagging the population growth with only 1% annual increase (1990-97) in grains contrast to 1.6% average population growth in developing countries (Hinrichsen and Robey 2000). There are some other factors including climatic variables (temperature, rainfall, humidity), proper fertilizers, water deficiency, genetic potential of the crop and other organisms which hamper the crop production. These organisms (insect pests) have been identified as a major constraint to increase productivity, especially for high-value crops and considered as serious threats to farmer's efforts in the pre- and post-harvest losses.

Insects play a significant role directly or indirectly and are indispensable part of the agriculture ecosystem. Insects are indeed the most flexible and adjustable form of life as their population far exceed than any other animals on the earth (Offor et al. 2014). For example, many insect species are bio-control agents, some are pollinators, decomposers or producers of valued products in the form of honey or silk. Others can play a significant role to produce pharmacologically active compounds like venoms and antibodies (Offor et al. 2014).

A pest is not only a biological entity rather it is an anthropomorphic categorization which is beneficial and harmful at the same time. For example, termites considered beneficial organisms in forests converting dead trees to organic matter and pests while feeding on wood having high economic value (Capinera 2001).

Crop losses from pests may be quantitative (reduced productivity) or qualitative (decline market value due to artistic features e.g. pigmentation), reduced storage features due to the contamination of the post-harvest products with pests or their toxic products (mycotoxins). Sometimes there is no clear difference between aesthetic and injury level especially in relation to horticultural crops; because a small depression or mark on fruit is insignificant blemish for grower but a conspicuous to down-grade the product for buyer causing significant economic loss to the farmers (Capinera 2001).

The occurrence of insects in every terrestrial and aquatic habitat makes them the most frequent and diverse population present on the planet. In agriculture, pests occur in a variety of groups including animal pests (rodents, insects, nematodes, mites, slugs, snails, birds), plant pathogens (viruses, viroids, fungi, bacteria, chromista) and weeds (undesirable plants). Food crops impairment has been caused by a vast numeric living things with 10,000 species of insect pests, 100,000 diseases (caused by different pathogens), 30,000 species of weeds and about 1000 species of nematodes (Hall 1995). Globally the estimated pre- and postharvest losses due to different insect pests, weeds and pathogens is believed to be 45% (Pimentel 1991) with an estimated worth of USD 500 billion, however, the figure would be more if no control measures had been used (Dhaliwal et al. 2004). The worldwide crop losses due to different pest categories may vary with the crop type, its geographic location, weather conditions, some year and the agronomic practices used. Additionally, the crop losses associated with abiotic factor, particularly the water stress, high temperature and nutrient supply may be reduced by adopting different agronomic practices.

1.1.2. Categories of insect pests

There are numerous insect pests and the estimated ratio of insects to humans is 200 million versus 1 and about 40 million insects for each acre of land (Pedigo and Rice 2009). Mostly insect pests can easily be assigned to groups based on characters on their wings or legs and mouth parts. Addition to this, their behaviour, how or where a pest feeds and other aspects of biology are key elements of pest categorization. The insect pests may be categorized based on injury i.e., primary or secondary and direct or indirect (Capinera 2001), frequency of occurrences i.e., regular, occasional, seasonal and persistent; while on population and damage level i.e., key, major, minor, sporadic and potential pests (Dhaliwal and Arora 1998).

1.1.2.1. Primary and secondary pests

Primary pests have potential of complete damage and breed in stable solid grains (e.g. whole healthy pulse and cereal grains) directly at some point during their life cycle. They have the capability to penetrate undamaged seed coat and advances towards the embryo to feed on the endosperm or cotyledons of the seed and reproduce very quickly when the conditions are favorable; grow into a large population and result considerable damage in a short period. Larger and lesser grain borers, rice, bean, pea and maize weevils are considered in stored grain primary pests. However, secondary pests do not attack the undamaged stored products instead generally breed and feed in those commodities that have been already attacked by some mechanical means or other pests (primary pests), bad milling, grinding, handling or other deliberate treatment of the commodity. Among secondary pests red flour beetle (*Tribolium castaneum* Herbst), rice moth (*Corcyra cephalonica* Stainton) and grain mite (*Acarus siro* L.) are important species that account for large proportion of invasion on already damage commodities (Farrell et al. 2002).

1.1.2.2. Direct and indirect pests

Direct pests are distinguished because they usually attack that part of the plant which is harvested for food and the effect, type of injury depends on the mouth parts possess by the insect pests i.e., biting and chewing or piercing and sucking types. Whereas indirect pest damages the other parts of the plant that is usually are not harvested for food purpose and their effect can be noticed in the form of reduced product quality, vectoring of disease and monetary loss. Direct infestation includes the stink bug (*Halyomorpha halys* Stal) feeding on tomato fruit; wireworms (*Agriotes* spp.) feeding on tomato roots and leaf minor on the foliage are considered indirect infestations (Capinera 2001). Although indirect pests are less injurious but a large population can cause a significant damage to the yield.

Regular pests

These pests occur frequently and have a close association with the crop e.g. rice stem borer (*Sciropophaga incertulas* Walk), brinjal fruit borer (*Leucinodes orbonalis* Guenee), pink bollworm of cotton (*Pectinophora gossypiella* Saunders), maize stem borer (*Chilo partell*us Swinhoe), sugarcane pyrilla (*Pyrilla perpusill*a Walker), whitefly (*Bemisia tabaci* Gennadius) and Jassid (*Amrasca biguttula* Ishida).

Occasional pests

The population of these pests is not frequent and have no close relation with the crop. For example, caseworm (*Nymphula depunctalis* Guenee) on rice and mango stem borer (*Batocera rufomaculata* De Geer), gurdaspur borer (*Bissetia steniellus* Hampson) on sugarcane and rice hispa (*Dicladispa armigera* Olivier) are considered occasional pests.

Persistent pests

These types of pests can be found on the crops all over the year and their control measures are much difficult. For example: guava mealy bug (*Maconellicoccus hirsutus* Green), chili thrips (*Scirtothrips dorsalis* Herbst), whitefly (*Bemisia tabaci* Genn.) and fruit fly (*Bactrocera* species).

Seasonal pests

Seasonal pests come during a specific season of the year e.g. mango hoppers (*Idioscopus* spp.) and red hairy caterpillar (*Amsacta albistriga* L.), pink bollworm of cotton (*Pectinophora gossypiella* S.) Citrus psylla (*Diaphorina citri* Kuwayama) and mango mealybug (*Drosicha mangiferae* Stebbins) occurs seasonally.

Based on the infestation percentage pests may be epidemic (abrupt outbreak in a severe form in a region at a particular time) or endemic (presence of pest at a low level regularly and restricted to a particular area).

Different parameters are associated with the level of insect pests population which include general equilibrium position (GEP), economic threshold level (ETL), economic injury level (EIL) and damage boundary (DB). General equilibrium position is the mean pest density over a prolonged period of time during which the pest population tends to vary because of abiotic and biotic factors keeping the permanent environmental conditions constant. Economic threshold level is the population density at which control measures should be initiated to limit the growing pest population that causes economic damage while EIL is the lowest population density that causes economic damage to the crop. Damage boundary is the lowest level of damage which can be measured and provides sufficient time for control measures (Dhaliwal and Arora 1998).

Key pests

These are the most serious and damaging pests. In this category of pests the GEP lies well above the economic injury level. A particular crop may be vulnerable to one or more key pests which may or may not differ regarding the season and area of the crop. Human involvement in the form of control measures may bring the pest population temporarily below the EIL. Being a persistent and high reproductive potential, they can rise back rapidly and for that repeated management practices including environment modifications may be required to lower their GEP below EIL and resultantly minimize crop damage e.g. codling moth (*Cydia pomonella* L.) on apple, cotton bollworms (*Pectinophora gossypiella* S., *Helicoverpa armigera* (Hübner), *Earias insulana* Boisduval, *Earias Vittella* Fabricius (Dhaliwal and Arora 1998) and fruit fly (*Bactrocera* species).

Major pests

In these types of pests, GEP is very close to EIL and sometime at the same level. Thus, there is a possibility of pest population crossing the economic injury level and for that economic damage can be prevented by repeated interventions of control measures. Generally, for most of the crops in most of the areas, major pests remain almost constant throughout the years. However, in some areas, the major pest species complex has been moderately varying from a long period of time e.g., cotton jassid (*Amrasca biguttula biguttula* Ishida), whitefly (*Bemisia tabaci* Genn.), rice stem borers (Dhaliwal and Arora 1998) maize stem borer (*Chilo partellu*s Swin.), sugarcane pyrilla (*Pyrilla perpusilla* Walk.) fall in this category.

Minor pests

The GEP reside below EIL and hardly cross EIL and DB for a short period of time under favourable environmental conditions. They may be restricted to specific crop plants or favour some other plants as hosts. Sometimes, a minor pest of a particular crop in one part of the world may be a major pest of same crop in other part of the globe. Minor pests comply available control measures and even a single application of insecticides is enough to avoid economic damage e.g. cotton strainers (*Dysdercus koenigii* F.), grey weevil (*Anthonomus grandis* Boheman), thrip and mite species (Dhaliwal and Arora 1998), dusky cotton bug (*Oxycarenus laetus* Kirby) and grasshopper species are minor pests.

Sporadic pests

The population of these pests is not significant and generally below GEP but sometimes under suitable environmental conditions at certain places they cross EIL and DB. Many sporadic pests including cutworms, grasshoppers, white grub are polyphagous with some oligophagous pests including sugarcane pyrilla (*Pyrilla perpusilla* Walk.), army worm (*Spodoptera litura* Fabricius) (Dhaliwal and Arora 1998) and gurdaspur borer (*Bissetia steniellus* Hampson).

Potential pests

Potential pests are not serious pests and do not cause any damage except any change in the cropping pattern, cultural practices and in the agroecosystem, that may push the GEP higher and cause economic damage. Based on their basic biology, only a minute ratio of the minor pests is also regarded as potential pests. For example, *Spodoptera litura* (F.) in North India (Dhaliwal and Arora 1998), rice hoppers

(*Nilaparvata lugens* Stal, *Sogatella furcifera* Horvath) and rice leaf folder (*Cnaphalocrocis medinalis* Guenee) are considered potential pest.

1.2. Losses by insect pests in agriculture

Since the beginning of agriculture, crop losses have been attributed to different insect pests. Biotic and abiotic environmental factors are the main cause of reduced plant growth and yield. Both qualitative and quantitative losses occur. Quantitative losses occur because of the reduced plant growth which leads a lower yield per unit area. While qualitative losses include the lower valuable ingredients contents and market value; for example due to aesthetic characteristics, reduced storage characters or the contamination of the harvested products due to pests or toxic products of the pests e.g. mycotoxins (Oerke 2006).

Identifying the type of losses caused by different insect pests is always complicated because insect pests when pass through various life cycle stages (instars) may damage different parts of the crop including roots, foliage, blossoms and fruits. Sometimes insect may not complete its typical damage because it may be disturbed from its location by a human activity, animals, strong winds or a bird might eat it. The resulting incomplete damage may provide an initial access to other organisms (e.g. bacterial rots) causing further damage or the scarred tissues continues to develop. The mouthparts of insect pests have a significant effect on type of damage; and is comprises on complicated toolkit of feeding with the basic elements the unpaired front labrum, a median hypopharynx behind the mouth, a pair of laterally attached mandibles and maxillae and a labium forming the lower lip. These component parts have been modified into a remarkable diversity of forms and well adapted over time that allow the insects as a group to exploit an extraordinarily wide range of food sources (Simpson 2013).

Although different species produce same type of damage but their mouthparts differs; hence the damage they have caused may serve as useful tool for the identification and classification of the pest. The mouth parts may be in entognathous condition in which the mouthparts lie in a cavity of the head produced by the genae, which extend ventrally as oral folds and meet in the ventral midline below the mouthparts (e.g., Collembola, Diplura and Protura). In some insect orders like Orthoptera, Coleoptera, Odonata and Lipedoptera etc the condition is ectognathous in which the mouthparts are not enclosed in this way, but are external to the head. The shape of the mouthparts is associated to diet, but two basic types can be well recognized: one modified for chewing and biting of solid food and the other adapted for sucking the cell sap (Simpson 2013). The types of damage to various crops can be direct or indirect. Direct injury done to the plants by eating on roots, leaves, flowers, seeds, burrows in stems and on fruits.

1.2.1. Damage to roots and tubers

About ninety percent of all insect pests spend at least some part of their lives in the soil (Gaugler 1988; Villani and Wright 1990; Kaya and Gaugler 1993) as it is considered as ideal niche and provides protection from extreme weather conditions and other natural enemies. These pests, irrespective of which group they fall, are members of several insect orders including Coleoptera, Lepidoptera, Diptera etc and others of equal importance. Some of the insect pests spend time in the dirt habitat several times during every season; some are constantly present, while others visit only once a year. Depending on the crop, soil insects can cause damage directly to the underground parts such as carrots, potatoes, sugar beets, onions, radishes, cereals and ornamental bulbs. The common soil pests which are vulnerable to below ground parts include wireworms, leather jackets, chafer grubs, cutworms, millipedes, vine weevil (*Otiorhynchus sulcatus* F.) larvae, cabbage root fly (*Delia radicum* L.), some species of slugs and snails and some other species of equal importance that cause damage from sowing to harvest (Wood and Cowie 1988). These insect pests enter and consume the fine root system, which directly kills the plant or indirectly decrease yield by lowering translocation of water and nutrients. Attack on root system can also enhance susceptibility to pathogens or lodging of mature plants. Because of tunneling in the roots, the lodging of plants especially the grains when touches the ground, soil fungi such as aspergillus may invade it. Similarly, root galling by several weevil species and roots swellings with root-knot nematodes resulted yellowing, wilting and ultimately lead to plant death (Offor et al. 2014).

1.2.2. Damage to leaves

Insect pests with chewing mouth parts may defoliate the plants by eating portion or whole leaves resulting skeletonize, notched, shot holed or shredding of leaves; while some other pests feed internally to the leaves or bore into the roots or stems. For example, the most common defoliating pests are locusts, grasshoppers, some species of weevils (Curculionidae), leaf beetles and some slugs and snails which feed on leaf margins and produce notches and in case of severe infestation the entire leaf lamina may be consumed. Similarly, the caterpillars, of several families (Noctuidae, Bombycidae, Gracillariidae, Hesperiidae etc.,) skeletonize, making tunnel mines or blotches and cut the lamina or making a leaf roll, respectively. While in case of pests with sucking mouth parts they usually cause foliage discoloration, curling, sooty mold production or twisting of young stems. For instance, aphids (Aphididae), whiteflies, mealy bugs (Pseudococcidae) and scale insects are regular sap feeders, retard the growth and ultimately lead to collapse of plants (de Jesus Jr. et al. 2001; Lopes and Berger 2001).

1.2.3. Damage to fruits and flowers

A diverse group of insect pests including caterpillars, aphids, weevils, moths, flies etc cause different type of damages to fruits reducing both yield and quality. For instance, larvae of mango weevil (*Sternochetus mangiferae* F.) and codling moth bore towards the core of mango and apple, respectively and cause severe damage (Sorensen 1988). The attack of pear midge on pear lefts fruitlets swell and cannot be developed properly and in most cases, drop prematurely. Similarly flower buds are often bored by caterpillar species (Noctuidae, Tortricidae) and eaten partially or completely by various grasshoppers. Sometime adults and larvae of beetles (Scarabaeidae, Chrysomelidae) causing ragged tiny holes to appear in the flower petals. Similarly, thrips (*Thrips tabaci* L.), earwigs (*Forficula auricularia* L.) and capsids attack on flowers resulting perforation and scruffy appearance to petals. In indirect type of damage, insects cause very little or no harm to the crop directly but spreads bacterial, viral or fungal diseases to the crops. For example, aphid transmits the viral diseases of sugar beets and potatoes (de Jesus Jr. et al. 2001; Lopes and Berger 2001).

Crop production may be enhanced in different areas of the world by introducing high-potential varieties, better soil and water management practices, fertilization and better agronomic techniques, application of pesticides, use of various biological and non-chemical control methods. Despite all these efforts to prevent injury, global crop losses to insect pests remain matter of concern. Pre-harvest pests account for an average loss of 35% of potential crop production around the globe (Oerke 2006). Moreover another 35% of the produce was lost during pre-harvest handling; transport, packaging, storage, processing and marketing (IWMI 2007). Total estimated crop losses may vary by context and scope. Loss may be differentiated into various levels, e.g., primary, secondary, direct losses, exhibiting that pests not only menace for crop production and diminish the net income of farmers but can also disturb the food supply and the economic status of individuals and even countries (Zadoks and Schein 1979). In context of food security, crop losses to pests may signify the comparable of food needed to nourish over 1 billion people globally (Birch et al. 2011). Although the losses vary among crops, locations and years; the aim of protection measures to minimize the damage and for that the available quantitative data on the effect of different categories of pests on different crops is very limited. Crop losses to various pests globally were first estimated by Cramer in 1967 and later on detailed losses assessment was done by Oerke et al. (1994) for major crops of the world. Regardless of crop protection measures, assessment of crop losses needed to be explained to develop future strategies to keep pest populations below damaging levels. While the productivity effects of such high crop losses are significant and over the past three to four decades the losses in all major crops have increased in relative terms.

Because of the paradigm shift in the new crop production technologies especially the crop protection approaches, Oerke (2006) and Popp et al. (2013) has revised the crop losses data for major cash and food crops for the period of 2001-03. Even though the actual losses due to various pests have been reduced considerably during the last few decades, however, the potential losses rate much higher in different cash and food crops (Table 1). In 2001-03 the estimated losses for soybean, wheat and cotton were 26-29% and 31, 37 and 40 per cent for maize, rice and potatoes respectively. Comparison to actual loss the potential loss rate was higher and for 2001-03 about 50-68% in wheat, soybean and maize, while 75, 77 and 82% were recorded in potato, rice and cotton respectively (Table 1.1). Although the number of crops covered in this analysis were limited, but giving some order of magnitude of losses for the future scenario of crop management in agriculture ecosystem. Pests were responsible for almost 50% losses of the crops in tropical region as compared to just 25-30% losses in Europe and the United States (Yudelman et al. 1998). Reasons for this greater level of damage in tropics is that pests are year-round problem moreover, farming community is often poorer and do not have access high yielding varieties of plants, effective and safe pesticides and adequate irrigation.

Table 1.1 Global estimates of actual and potential crop losses due to pests of major crops

Crop	Actual loss rate (%)			Potential loss rate (%)		
	1988-90	1996-98	2001-03	1988-90	1996-98	2001-03
Cotton	38	29	29	84	82	82
Rice	51	39	37	82	77	77
Potato	41	39	40	73	71	75
Maize	38	33	31	59	66	68
Soybean	32	28	26	59	60	60
Wheat	34	29	28	52	50	50

Source: *Oerke et al. (1994), Oerke and Dehne (2004), Oerke (2006), Popp et al. (2013).*

1.3. Overview of pest management strategies

1.3.1. Pre-insecticide era

Pest dilemma is as old as the beginning of crop cultivation and actions to alleviate these problems started right from the pre-historic days. Some traditional approaches including cultural and mechanical practices (ploughing, crop rotation, flooding, field sanitation etc.) were among the oldest pest control methods developed by farmers with their own experiences (Smith et al. 1976). These were followed by use of sulfur with stored grain, about 2500 B.C. by Sumerians. Both Egyptians and Chinese were presumably the pioneers in the use of botanical pesticides for the protection of seeds, stored grains and other field crops. However, about 300 B.C., some advancements were occurred in pest control including the timely planting of crops to avoid losses and the use of natural enemies to control pests (e.g., in China ants were used to control leaf beetles on citrus). Some new developments were recorded in pest control strategies until about 1000 A.D. and later 1100 A.D. insecticidal soap were used in China. While in 1600's tobacco infusions, arsenic and some herbs were applied against insect pests and late during 1700's, some plant resistance to insects was progressed in Hessian fly, *Mayetiola destructor* (Say) in the USA. In 1705, mercuric chloride was used as a wood preservative and about hundred years later the inhibition of smut spores by copper sulfate was proposed by Prevost. Later, in 1850's very important natural insecticides rotenone and pyrethrum were developed from different plant parts and used for a longer period of time. To control gypsy moth (*Lymantria dispar dispar* L.) lead arsenate was used in 1892. During the late 1800s and early 1900s, there was rapid development in synthetic insecticides and pest control focus was slowly shifted from ecological and cultural to chemical control. In the beginning, the insecticides were expensive, hazardous to apply, phytotoxic and were not efficient compared to today which are well targeted and goal oriented.

1.3.2. Insecticidal era

The discovery of the insecticidal properties of DDT (dichlorodiphenyl trichloroethane) during the late 1930s by Swiss chemist Paul Muller marked the beginning of insecticidal era and had a great impact on insect pest control. In its early days, it was acclaimed a miracle due to its toxicity to wide range of insect pests, persistent nature, inexpensive, effective and easy to apply (Pedigo and Rice 2009). After worldwar II, there was diverse and rapid development in the insecticide industry to increase food production and for that several insecticides such as hexachlorocyclohexane (HCH), aldrin, dieldrin, parathion, schradan, toxaphene, chlordane, heptachlor (organochlorine group) and allethrin (synthetic pyrethroid) and other organophosphates and carbamates in the following periods. Many petroleum companies have been involved in the development of chemicals and during the 1950s other organophosphates and carbamates entered the insecticide industry. The first organophosphorus insecticide developed was Malathion having a relatively very lower toxicity to mammals. Phenoxyacetic acid herbicides were also discovered during the same time period. An important breakthrough in the field of plant chemotherapy occurred in late 1960s with the introduction of some new effective systemic fungicides in the market. Most of the 1950s chemical industries and farmers were not fully aware of the health hazardous problems associated with the use of pesticides. However, indiscriminate use of pesticides was the main reason of the problem and in 1962 these were pointed by Rachel Carson in her book "Silent Spring". The book recounted how the DDT residues in the food chain can be dangerous for the living organisms. In the meantime, along with these developments, the number of insect species showing resistance to insecticides including DDT, organophosphates, carbamates and pyrethroids had been increased rapidly with the passage of time. The ubiquitous use of pesticides in the ecosystem, their high residue levels in food products and the rising cost provided the necessary action for the limiting pesticide use and open the doors for the safest and more environment friendly idea of pest management (Pedigo and Rice 2009).

1.4. Insect pest control paradox

Pest outbreak is one of the most serious problems in agriculture and the analysis over the past few decades had showed that the proportion of crop losses to insect pests increased significantly. Historically pest management has been studied both pragmatically and theoretically and in most of the cases pesticides have been used to suppress the pest population. There is a very interesting scenario of rising pesticide use, rising crop losses to pests and most significantly the increase of crop production. Experiments in Pakistan concluded that the use of herbicides had prevented 23 percent crop losses (Qureshi 1981), while some crops would have been destroyed without use of chemical pesticides (Farah 1994). According to another analysis, global losses would have been raised from 42 to 72 percent in the absence of pesticides (Oerke et al. 1994). However, pesticides have been effective at certain times to suppress pest population but can be an outbreak for the insect pests other times (Matsuoka and Seno 2008) resulting in a population well beyond the crop's economic threshold. This situation has been to refer as paradoxical phenomenon of increased pesticide use and often considered as pest resurgence. Many investigations had been carried out regarding pest resurgence (DeBach et al. 1971; Gerson and Cohen 1989; Hardin et al. 1995; Cohen 2006) that could be due to the development of resistance in the pests against pesticides or by the decrease of its natural enemies affected by the pesticides (Morse 1998). The timing of the application of pesticides is the key (Li Charles and Young 2013), however a regular application is not a good control option to suppress the pest population (Hamilton 2008). The answer to the paradox of increased pesticide use and rising crop losses to pests lies in the integrated management which was originally coined to define the blending of biological control agents with synthetic insecticide control options (Bartlett 1956). Certainly, the use of pesticide is an important tool to suppress pest population and many pest management programs depends on pesticides use. Geier and Clark outlined the idea of pest management and called this concept protective population management in 1961, and it was later termed as pest management (Geier 1966). Pest management varies from previous approaches which were focused on control rather than to manage the pest populations and bringing the injury to a tolerable level. Since its commencement in 1972 the term integrated pest management was recognized by the scientific community after the report publication by the council on environmental quality (CEQ 1972).

1.5. Concepts and components of sustainable pest management

We consider simply the sustainable agriculture is the food production using farming techniques that balance with the environment and favorable both to humans and other species (Harwood 1990). For a sustainable pest management system, these farming techniques must be economically viable and contribute to a healthy environment for long term. The key approach for pest regulation that we predict is the consistency with these goals for sustainability as it is clearly obvious in integrated pest management programs. There are many definitions for Integrated Pest Management (IPM) suggested by different authors. Pest management is the selection and the use of pest control multiple tactics that will ensure the favorable ecological, economic and socioecological consequences. The basic hypothesis is that IPM is very important for sustainable management of animal pests, plant pests and weeds which cause threats to the quality and quantity of agricultural products. The principles of pest management clearly emphasize conservation that contains both cropping and nonagricultural environments (water, air, soil, wildlife etc.,) (Pedigo and Rice 2009). Moreover, the IPM success largely depends on farmer’s knowledge about the awareness of pests’ biological and ecological processes that are much critical to use different options to solve the problem (James et al. 2010).

Agro-ecosystems is considered a habitat of less diversity of animal and plant species compared to natural ecosystems e.g., forests and meadows. Agricultural ecosystems can be more susceptible to pest attacks and resurgence due to lack of diversity both in plant and insect pest species compared to natural ecosystem. However, much can be gained through the manipulation of different production techniques to minimize pest problems and for that a considerable knowledge requires about the pests and factors that affect their populations. For insect pest management, planning should anticipate pest problems to follow the ways to avoid them (Pedigo and Rice 2009).

Different authors have proposed pest management practices differently with slight variations. Geier (1966) suggested the following management practices: (1) how the pest life system can be modified to reduce its population below economic threshold level (2) applying biological knowledge and current technology to achieve the modification and (3) development of pest control procedures suited to current technology and compatible to economic and environment aspects. Similarly, Apple et al. (1979) listed the components of pest management as follows; (1) pest identification to be managed (2) specify management unit (3) development of pest management strategy (4) development of monitoring techniques (5) establishment of economic thresholds and (6) develop descriptive and predictive models. A pest management approach is the plan to mitigate or eliminate a pest problem and is always depends on the insect biology and the cropping system involved.

There are different types of strategies suggested by Pedigo and Rice (2009) that can be followed: (1) no intervention or involvement, (2) diminish pest numbers, (3) decrease crop vulnerability to pest damage, and (4) reduction in crop susceptibility along with pest number. The use of multiple strategies is a basic and key principle of designing insect pest management programs. However, the appropriate strategy primarily depends on the status of insect pest in the production system. Broadly speaking, the major subdivisions of insect pest management programs are preventive and therapeutic practices. Integrating these tactics in a comprehensive manner has been essential for sustainable pest management but with a few limitations associated to these practices. Although using a single tactic may be successful for a short duration but by integration of these practices might provide safe guards against ecological disruptions (pest resistance or destruction of natural enemies) that often develop because of widespread reliance on a single strategy (Pedigo and Rice 2009).

1.5.1. Preventive strategy

Preventive strategies are primarily used for insect pests that cannot be controlled effectively after injury and for that action should be taken before they become an economic problem. These practices often employed without the knowledge of pest presence or status of the pest population. Prevention can be accomplished by focusing either on the pest or the host. In most of the times available practices focus on the pests to reduce average population density or general equilibrium position of pest and afterwards level of crop damage to a below economic injury level. Most of the above mentioned agronomic practices are critical in pest management, since the intensity of the pest problem is often directly related to these practices. Majority of the techniques that accept and utilize ecological factors are compatible with other for integrating into an overall preventing pest management program. It is also very important to know that making decisions of insect pest management should be placed in context with other factors e.g., natural enemies of pests (predators, parasitoids and pathogens), weather etc. Therefore, the estimation of insect pest densities and/or the amount of crop injury should be accompanied by evaluation of the potential impact of natural enemies and impending weather conditions.

The other area of preventive pest management is the crop itself in which efforts can be made to reduce losses by making the host less vulnerable or tolerant to insect pest population. The sowing of plant tolerant varieties to pest injury is a tactic which has been often ignored by the breeders, since it is an important method to develop ability in plant to withstand despite injury. Plant tolerance in integrated pest management programs with the existing cultivars can be achieved by growing healthy plants through proper agronomic practices e.g., irrigation, fertilization. Additionally, plant and animal quarantine is a key component of preventive pest management and play an important role by preventing spread of pests from infested to uninfested areas.

1.5.2. Therapeutic strategy

In ecological based pest management strategies, therapeutics may have a noteworthy role and recognized as a key component of IPM programs to cure a chronic crop disorder and to prevent future losses. Instead of primary lines of defensive therapeutic controls should be regarded as backup components. Curative strategies usually focus on timely assessment of pest populations and reaction to them with the use of therapeutic materials, if the density of an insect pest population has reached or exceeded the economic threshold level. As therapeutics, synthetic natural products and living organisms can be regarded as an efficient tool, however, whether product is nontoxic or natural based does not inevitably mean it is less disruptive than synthetic products. The key is to work in an integrated way as much as possible and for that number of therapeutic products (e.g., biopesticides, semiochemicals and natural enemies) are prevailing and many more are being advanced with new technological measures (Lewis et al. 1997). However, all suitable non-chemical control options should be implemented before pesticides are recommended. There are number of tactics that can be applied in pest management therapy including selective pesticides, fast-acting nonpersistent biological controls (microbial insecticides), early harvests and mechanical removal of pests (Pedigo and Rice 2009). Of these available practices, pesticides are by far the most important in pest management treatment. For the development of pest management program, both preventive and therapeutic tactics should be integrated in a way that ensures the economically and ecologically sound outcomes.

1.6. Conclusion

Crop pests, pathogens and weeds are considered significant challenge to world food security, poverty alleviation and agricultural earnings. It has been well recognized that the modern-day agriculture cannot withstand the current crop production levels and standards with the exclusive use of pesticides. Increasing pest problems and ecological backlash can only be corrected using holistic pest management practices including preventive and therapeutic tactics. Recent expeditions are for effective, safe and long-term pest management strategies which have been targeted principally towards the advanced and improved products attributed as a substitute of existing conventional toxic synthetic pesticide. To increase the yield and to address the future production demands IPM, will be considered the most attractive pest management approach when pesticides repercussions are taking into account. Although, the results of integrated pest management sometimes variable and insidious. However, this approach can better exploit the modern science and the traditional agricultural systems based on indigenous farming practices for the sustainable crop production. The primary goal of integrated pest management is to increase the rate of new findings to address both chemical and non-chemical research areas and develop the farming practices that are compatible with ecological and conservation systems and scheming the cropping pattern that certainly limit the advancement of any organism to become a pest. Understanding the agro-ecosystem, integration of new management skills and the new concepts for pest management must be encountered so that we can protect our environment smartly and make sure the uninterrupted safe and nutritious food supply for the growing world population.

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Chapter 2

Principles of Insect Pests Management

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Abstract

A successful and sustainable pest management depends on the knowledge of the strategy, pest biology and pest ecology in agroecosystem. The development of an effective pest control strategy is reliant and contingent on ten pillars including: 1) correct identification of the pest and its pest-status; 2) determination of pest ETL; 3) knowledge of the available control tactics; 4) selection of control tactic(s); 5) decision of appropriate timing (when?), conducive technique (how?) and targeting site (where?); 6) determination and choice of the pest control goals; 7) selection of effective pest monitoring tool/techniques; 8) identification of factors causing failure of pest control tactics; 9) public awareness and long-term commitment; 10) planning for and improvement in in pest management strategies. A comprehensive knowledge of various pest and ecosystem associated aspects like pest population ecology and dynamics, pest population structure and interactions and structure, function and regulators of ecosystem is compulsory for determining an appropriate pest management strategy. Based on aforementioned information, appropriate strategy can be selected and implemented from already well defined four strategies including 1) "Do-Nothing Strategy", 2) "Reduce-Number Strategy", 3) "Reduce-Crop-Susceptibility Strategy" and 4) "Integrated-Strategy" to cope with the emerging or

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prevailing pest condition. This chapter highlights the basic concepts and principles of sustainable pest management that are based on well-defined goals, estimates of population size, evaluation and comparison of available management options and monitoring as well as evaluation of practiced management activities/strategies regarding benefits and costs. Defined goals determine better and appropriate available management options in a prevailing situation; population estimates help in determining action threshold and deciding timeframe for initiation necessary actions. Effectiveness of available control options in stipulated time-period, environmental and social consequences and cost-benefit-ratio can help in ranking out the efficient, economical and ecofriendly management strategies. This chapter focuses on the fundamental concepts and principles, practical strategies and various techniques of insect pest management.

Key words: Concept and principles; Pest monitoring and scouting; IPM theories; Decision levels; Cost-benefit-ratio

2.1. Introduction

Every organism interacts with biotic and abiotic components of ecosystem and struggle for its better survival and existence in nature. Different types of interactions exist between pests and other components of ecosystem, especially human, plants and animals. These interactions can create issues of competition for food and space; endemic or epidemic outbreak of diseases/ nuisance, damage to properties and injury to both plants and animals. Pest incidence as well as its population dynamics and control are regulated in such interactive agroecosystem by many forces and factors. The major of these are forces of destruction like environmental resistance, forces of creations like biotic potential and characteristics or components of an agroecosystem. A comprehensive knowledge of destructive forces including abiotic stresses (adverse environmental conditions/density independent factors), biotic stresses (density dependent factors like predators, parasites, pathogens, competitors etc.) and biotic potential (reproductive potential, survival potential, nutritive potential and protective potential) (Fig. 2.1) help us decide whether the time is to adopt “Do-Nothing Strategy”, “Reduce-Number Strategy”, “Reduce-Crop-Susceptibility Strategy” or “Integrated-Strategy” to manage the indeginous and exotic emerging pest problems (Pedigo and Rice 2009; Schowalter 2011).

Pest management is a two-strand approach which mainly relys on the knowledge of the strategy, pest biology and pest ecology in agroecosystem (Fig. 2.1). The selection of appropriate pest control technology as well as its effective and efficient application mainly depends upon a comprehensive knowledge about it. The biological and ecological knowledge of pest helps to determine the most appropriate procedure/method (How), timing (when) and place (where) for effective use of any technology and economically effective management of any pest (Buurma 2008). Various aspects of any technology which lead towards its proper and effective application include:

- Nature and type of technology
- Method of its application (aerial, foliar, chemigation, baits, traps etc.)

- Durability of the technology
- Equipments and accessories needed for its implementation
- Performance limiting factors of technology
- Compatibility of technology with other available management tools
- Specificity of the technology (broad spectrum or target specific))
- Mode of action

(Pedigo and Rice 2009)

The knowledge of various aspects of biology and ecology of pests lay the foundation of an efficient and economical pest control strategy is important for achieving key objectives of pest management. For examples, suck kind of knowledge reduces the threat of crop failure by endemic or epidemic pest outbreak. Such knowledge also strengthens the effectiveness of pest control strategies, reduces operational cost of technique used, enhances productivity and profitability by reducing the amount of inputs and ultimately eliminates or reduces the threats of environmental degradation and hazards of human health (Knipling 1979; Norris et al. 2002). Various aspects of pest's biology that can be helpful in devising efficient pest management strategies include:

- What kind of habitat does the pest prefer? (Darkness, indoor, outdoor, humid, warm, temperate, aquatic, terrestrial etc.)
- What kind of food does the pest prefer?
- What is the total life span of pest?
- What is longevity of incubation period of the pest?
- Where are different life stages found?
- What is the breeding place and season of the pest?
- What kind of behavior does the pest exhibit in its life?

(Trivedi 2002; Pedigo and Rice 2009; Jha 2010)

Integrated application of multiple and highly compatible tactics; reduction in number or effects of pest below defined economic decision levels (EIL and ETL); and conservation of environmental quality are the key characteristics/elements of sustainable pest management (Pedigo and Rice 2009). However, Geier (1966) suggests some supplementary characteristics/elements of sustainable pest management system and deliberates that a pest management technology/system should be: 1) highly target specific i.e., very selective for pest and safe for nontarget organisms ; 2) Comprehensive and conducive for crop productivity (not be phytotoxic and enhance plant-growth and yield); 3) highly compatible with the key principles of ecology and 4) tolerant to potential pests but within economically tolerable limit. A comprehensive and practical knowledge of above-mentioned elements guarantees the development of an ecofriendly, economical and efficient, crop production and protection program (Buurma 2008; Alam 2010; Schowalter 2011).

Effective and sustainable insect pest management also depends on economic decision levels which are mendatory for determining the course of action, ensuring sensible pesticide application, reducing unacceptable economic damages, safeguarding the profits of producer and conserving the environmental quality in any pest situation (Alam 2010; Jha 2010).

This chapter highlights the basic concepts and principles of sustainable insect pest management which are based on well-defined goals, estimates of population size, evaluation and comparison of available management options and monitoring as well as evaluation of practiced management activities/strategies regarding benefits and costs. Defined goals determine better and appropriate available management options in a prevailing situation; population estimates help in determining action threshold and deciding timeframe for initiation necessary actions. Evaluation and comparison of available management options, their effectiveness in stipulated time-period, environmental and social consequences and cost-benefit-ratio can help in ranking out the efficient, economical and ecofriendly options. Monitoring as well as evaluation of practiced management activities/strategies on the basis of benefits and costs is too imperative for improved adaptive management. All the principles of pest management are described.

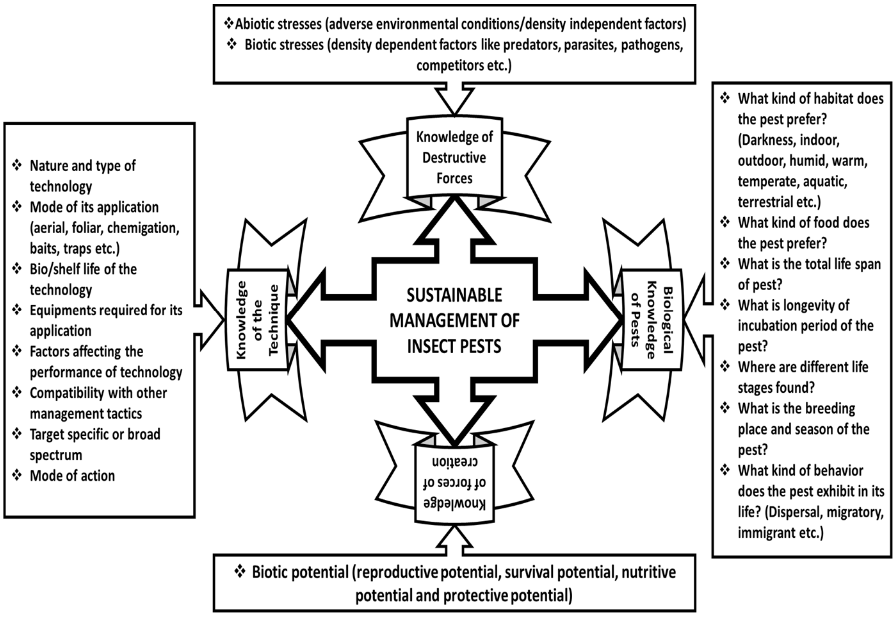

Fig. 2.1. Four pillars and their associated components which lay down the basis of sustainable management of insect pests.

2.2. General Principles of Pest Management

The era of conventional crop production and protection has turned to ecofriendly and organic crop production and protection system where natural products based techniques are employed in the agricultural industry and toxic chemicals based techniques are being depleted from the agriculture system. A sustainable agroecosystem system composing of healthier and more productive crops with least utilization of toxic pesticides depends upon a holistic pest management approach (Joshi 2006; Dhaliwal and Koul 2007; Singh 2008) which is based on following basic principles (Fig. 2.3).

2.2.1. Pest avoidance/exclusion

It is kind of precautionary step which inhibits the entry of any insect pest into any agroecosystem and ensures pest free zone. This principle is based on the utilization of such techniques or practices which exclude and prevent the pest and it is always considered as a foundation step of any IPM program. Pest avoidance or exclusion techniques include hand-picking, screening, bagging, physical beating, banding, trapping, acausting (noise creation), physical barriers, burning, sieving and winnowing and rope dragging, etc., (Dhaliwal et al. 2006).

2.2.2. Hand-picking

Hand picking is kind of excluding technique which is not practicable for large scale pest management program; however, it can be practiced for small scale pest management program like in lawns, kitchen gardening, small-scale tunnel farming, inside greenhouses. This technique is the most practical way in certain conditions like, when cheap labour is available, insects and their eggs/egg-masses are large and conspicuous, insects are too sluggish, have congregating behavior and are easily accessible to the pickers. Handpicking of slow moving and visible larvae of *Pieris brassicae* (L.) (Cabbage butterfly) (Lepidoptera: Pieridae), lemon butterfly [*Papilio demoleus* Linn. (Lepidoptera: Papilionidae)], semiloopers and loopers (Lepidoptera: Noctuidae), cutworms (Lepidoptera: Noctuidae) and red pumkin beetle [*Aulacophora foveicollis* Lucas (Coleoptera: Chrysomelidae)] and visible eggs/egg-masses of cabbage butterfly, armyworm [*Spodoptera* (Guenee) and *Mythemna* (Ochsenheimer,) spp. (Lepidoptera: Noctuidae)], and borers [Pyralid borers, Noctuid borers, Crambid borers etc. (Lepidoptera)] is an easiest, direct and excellent method of controlling them especially when their infestation is restricted to only a few plants. In case of pink bollworm [*Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae)] infestation in cotton, the rossetted flowers having pink bollworm larvae inside are picked and destroyed. Collection and destruction of egg masses of top borer [*Scirpophaga nivella* F. (Lepidoptera: Pyralidae)] in ratoon and seasonal sugarcane (*Saccharum officinarum* L.) crop reduces its endemic outbreak and losses. For reduction in incidence of gurdaspur borer [*Acigona steniellus* Hamp. (Lepidoptera: Pyralidae)], area-wide collection and destruction of infested canes harboring its gregarious larvae proves very effective. Deep burying or chemical treatment of fallen fruits reduced the incidence and periodic outbreak of fruit flies in orchards. This conventional and oldest technique helps to collect and destroy the adults before they start laying their eggs, to gather and crash the eggs before they hatch, to pick and kill the larvae/nymphs before they cause economic losses and ultimately prevents the build-up of pest population and the resulting damage. Clipping and destruction of rosetted flowers infested with *P. gossypiella* larvae, withered top infested with spotted bollworm [*Earias* spp. (Fab) (Noctuidae: Lepidoptera)], splayed squares along with sheded fruiting and floral bodies attacked by bollworms, leaves having egg-masses or army of younger larvae of armyworm (*Spodoptera* spp.) and tobacco caterpillar [*Spodoptera litura* Fabricius (Lepidoptera: Noctuidae)] can minimize population buildup and extent of cotton damage by these insect pests (Saha and Dhaliwal 2012). Further outbreak and infestation of khappra beetle [*Trogoderma granarium* Everts (Coleoptera: Dermestidae)] can be reduced if its clustered population is collected and destroyed.

2.2.3. Avoidance/exclusion by bagging, screening and barriers

Bagging, screening and barriers installation is also considered very useful for protecting the crop and fruits from attack by insect pests as well as for keeping away the insect pests which either act as carrier or vectors of various fatal diseases in animals and man or create nuisance for man. For example, field bags' dragging in the maize (*Zea mays* L.) or sorghum (*Sorghum bicolor* L.) field and sugarcane (*S. officinarum* L.) ratoon crop (April/May) to collect sugarcane pyrilla [*Pyrilla perpusilla* Walker (Homoptera: Lophopidae)] can reduce the chances of their massive migration from maize/sorghum to sugarcane and population buildup of pyrilla at the initial growth stage of sugarcane ratoon crop. Such type of field bags can also be used for the mass collection of various grasshoppers (Orthoptera: Insecta), bugs (Hemiptera: Insecta), crickets (Orthoptera: Insecta) and other minute, small and large insects harboring vegetation. Wrapping of individual fruits with paper bags, polythene bags, butter-paper bags or net bags protects 95% of these fruits from the infestation of fruit flies. Covering whole small trees with any transparent material can reduce the attack of various insects' pests. Construction of water filled or dust (insecticide) treated drench between wheat (*Triticum aestivum* L.) field and burseem (*Trifolium alexandrium* L.) field can reduce the migration of armyworm (*Spodoptera* spp.) larvae from wheat to burseem fields and minimize their damage on burseem. Similar type of drenches can reduce the migration of bands of locust hoppers [*Schistocerca gregaria* (Forskål) (Orthoptera: Acrididae)] from the breeding placed to nearest field crops. Application of various types of bands around the tree trunks reduces the upward crawling of various crawling insects and protects their damage to leaves, floral parts and fruits. Sticky bands or funnel type bands installed around the stem of mango tree as a barrier for upward crawling mango mealybug [*Drosicha stebbingi* Green (Hemiptera: Margarodidae)] stop its nymphs below the bands and protect its damage to inflorescence, tender leaves and mango fruits. Yellow sticky traps are used for the management of aphids (Homoptera: Aphididae) on various crops. Red colored spherical traps are used for the control of fruit flies in orchards. Screening of windows, ventilators and doors of rooms and sheds with fine meshed wire gauze keep the house flies [*Musca domestica* L. (Diptera: Muscidae)], mosquito species [*Culex* spp., *Aedes* spp. (Diptera: Culicidae)] and other insect away from human being and animals which remain protected from the insect borne diseases and nuisance. Heavy irrigation followed by rope dragging on crop cultivated on small scale help to shed away the larger wingless insects or their stages with or without infested plant parts especially flowers, bolls, fruits etc. from the plants into the water and are killed by drowning in water contaminated with insecticides.

2.2.4. Avoidance/exclusion by trapping, shaking, sieving and winnowing

Trapping tactic is widely used for the management of insect pest of various economical crops. Various types of traps including light-traps, pheromone-traps, bait-traps, suction traps etc. are used in trapping technique which is being used for monitoring, mass trapping, mating disruption and management of various types of insects. For example, pheromone traps are being practiced successfully for the monitoring, trapping, mating disruption and management of pink bollworm (*P. gossypiella* Saunders), gypsy moth [*Lymantria dispar* (L) (Lepidoptera: Lymantriidae)], cotton grey weevil [*Anthonomus grandis* Boheman (Coleoptera: Curculionidae)], pine beetle [*Dendroctonus ponderosae* Hopkins (Coleoptera: Curculionidae)], oriental fruit fly [*Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae)], melon fruit fly [*Bactrocera cucurbitae* Coquillett (Diptera: Tephritidae)], European chaffer [*Rhizotrogus majalis* (Raz.) (Coleoptera: Scarabeidae)] (Fig. 2.2). Light traps associated with toxic compound are practiced for the trapping and killing of nocturnal insects pests. Bait-trap consisting of food source as kairomone and odorless insecticide as killing agent is used for attraction, trapping and killing of various insects. GF-120 food-bait is used for the management of fruit flies in orchards and cucurbits crops. Placing chopped turnips (*Brassica rapa* L.) or potatoes (*Solanum tuberosum* L.) in form of heap in cutworms (Lepidoptera: Noctuidae) infested crop provide a site of attraction and aggregation for cutworm larvae. From such heaps, the aggregated cutworm larvae can be collected and destroyed. Air-suction trap and tractor mounted light-plus-air suction traps can be employed for attraction and killing of various soft bodies small insects like whiteflies [*Bemisia tabaci* Genn. (Homoptera: Aleyrodidae)], thrips [*Thrips tabaci* Lindeman (Thysanoptera: Thripidae)], winged aphids, adults of Dipteran and Lepidopteran leafminers [*Liriomyza trifolii* (Burgess) (Diptera: Agromyzidae); *Phyllonorycter* spp. (Lepidoptera: Gracillariidae), *Eriocrania spp.* (Lepidoptera: Eriocraniidae), citrus leafminer [*Phyllocnistis citrella* Stainton (Lepidoptera: Phyllocnistinae)], adults of psyllids [(Homoptera: Psylloidea) like *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae)] etc. The sluggish or immobile insects including mealybugs, aphids, psylids etc. can be separated from the plants/tree-canopy in case of small scale cultivation, kitchen gardening or landscaping by simple shaking and jarring technique. This technique can also be used against locust and defoliating beetles on small scale. Inside the godowns or any storage structures, various life stages of insect pests of stored grains can be separated, collected and destroyed by sieving and winnowing technique.

2.3. Identification of pest and its status: Tools and techniques

Identification of pest, its various life stage and its effects is considered the key components of any integrated pest management plan. An accurate identification of pests helps to determine their pest status, population dynamics and effective control measures. However, an accurate identification of prevailing pest species at the spot is a challenging and difficult step too even for any qualified and expert entomologist. Continuous and constant efforts to recognize the prevailing pest species makes correct identification of pests of a particular crop comparatively easier.

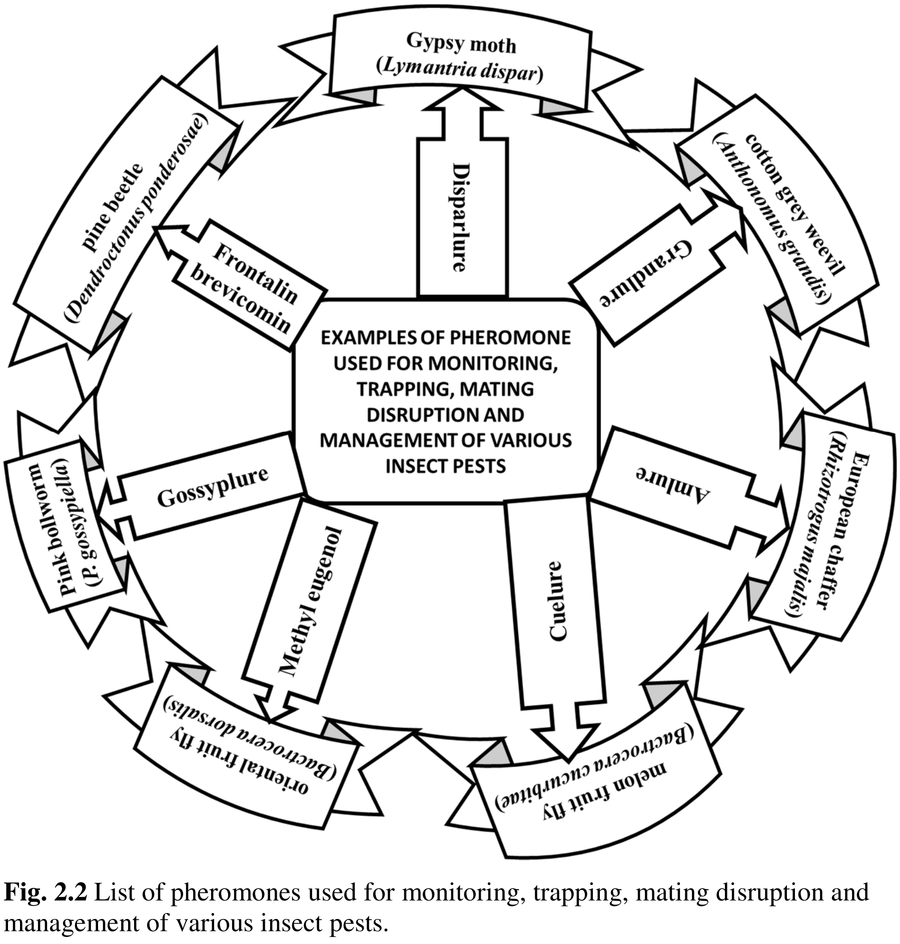

Fig. 2.2 List of pheromones used for monitoring, trapping, mating disruption and management of various insect pests.

2.3.1. Strategies to identify pest species

Several approaches can be used for an accurate identification of useful and harmful insects. The catches can be compared with pics/images available on the internet websites or in compendium/books. The collections can be sent to expert insect taxonomists or entomologists who can identify insects and explain various questions related to the identified pest. Other strategies include hiring entomologists from local colleges, universities, or pest management companies (pesticide organization) or getting training from these organizations for exact identification of pests. After an accurate identification of the catches, reference collection should be maintained for future identification and training of the other stakeholders.

2.3.2. Magnification

For the exact identification of small or minute insects, 15-30 X magnification lens are required. Hand held magnifiers can be used for magnification and identification of small or minute insects.

2.3.3. Identifying insect debris and damage

Some insects are very difficult to observe, locate and identify because they mostly remain hiding during daytime and are active for very short period of time or during night. The presence of such insects can be determined based on their debris, damages, remnants, products etc. An intense vigilance is needed. For example, life stages of silverfish [*Lepisma saccharina* L. (Thysanure: Lepismatidae)], booklice (Psocoptera: Insecta) and other insects are difficult to locate due to their small size, camouflaging color and reclusive habits. The following signs can be used to recognize the commodities under attack of insects:

2.3.4. Insect remains

Sheded wings of termite, casing of larvae, exuvia of molted insects, dark egg pods of cockroaches, webbing of clothes moths [*Tinea pellionella* L. (Lepidoptera: Tineidae] are some prominent examples the signs which can be used for identification of insect pests.

2.3.5. Frass

The product of the insect's feeding and digestion is termed as frass. For example, sawdust collected in the excavated holes indicates the damage of powderpost beetle. Mud tunnels on any surface indicate the incidence and damage of termites. The frass color mostly resembles with color of digested food. The presence of frass every time below the infested object is probably the indication ofactive population of infesting insects.

2.3.6. Visible damage

Feeding damages are visible symptomologies which ensure the incidence of insect pests. The more prominent visible damages include enterrance and exit holes in damaged object or commodity. Presence of clothes moths (*T. pellionella* L.) may be concentrated on damaged spots on strata. Skinned paper is the indication of occurrence and grazing of silverfish (*L. saccharina* L.). The activities of wood boring insects can be detected by the exit holes which indicate the damage has already been and adults emerging from the pupae have been escaped.

2.3.7. Smell and sound

Smell of faeces and decaying byproducts of feeding and digestion by insects also indicate their activities and incidence. Similarly, when insect perform feeding and other life activites, they produce specific sound. Such smell and sounds are detectable and can be perceived and heard, respectively by human. The activities of wood damaging beetles and can be confirmed by hearing special sound produced wood boring insects. The incidence of cockroaches can be defined by their pungent smell. The presence of termites and hollow tunnels/areas under the wood surface can be detected by gently tapping with finger across it and listening the differences in sound produced.

Examples of insects' identification strategies

1) The adults of termites (Insecta: Isopter*a*: Kalotermitidae) consume wood or woody materials and create muddy tunnels or hollow areas internally under the wood. Termite activities do not appear in form of flight/exit holes rather sand-like frass and muddy tunnels towards the cellulosic food source (furniture, books, wodden-frames, etc.,) (Peterson et al. 2006).

2) After hatching from eggs, the larvae of woodboring beetles including powderpost beetles [*Xylopsocus capucinus* (Fabridius) (Coleoptera: Bostrichidae)] and death watch beetles [*Xestobium rufovillosum* de Geer (Coleoptera: Anobiidae)], tunnel through the wood and consume it till the emergence of adults through exit holes. A talcum-powder like very fine frass is produced when powderpost beetle consumes wood or woody materials (O'Connor-Marer 2006; Lewis and Seybold 2010).

3) Dark places with high humidity and starch stocks are preferred by Silverfish (*L. saccharina* L.) Skimmed papers and other starchy materials indicates its incidence (Nasrin 2016).

4) Larvae of carpet beetles [*Anthrenus flavipes* (LeConte) (Coleoptera: Dermestidae)] prefer to graze across the surface of fabric-stuff, plant materials, fur/fleece, and feathers and its damage generally gives a shabby/ragging look to the damage material.

5) Dermestids include larder beetle [*Dermestes lardarius* Linnaeus (Coleoptera: Dermestidae)] and hide beetles [*D. maculatus* DeGeer (Coleoptera: Dermestidae)]. These beetles are very voracious feeders and their larvae voraciuosly devour skins of animals and dried plants or their materials

6) Identification of case making clothes moths (*Tineola pellionella* L.) larvae can be easily accomplished by the cases spun around their bodies from the materials they feed on. Similarly, the incidence and damage of webbing clothes moth [*T. bisselliella* Hummel (Lepidoptera: Tineidae)] larvae can be identified by the silk trail they leave when they move to feed on food.

Both the moth are voracious feeders of woolen-materials, dried woody materials, feathers and fur. Their feeding results in gradual-thinning of the damage materials which can be used as indicators of their attack.

7) A tiny pale colored booklice (Psocoptera: Insecta) feed mostly on mold, fungi present in books and on papers. They also feed of dead and decaying insect.

8) Bookworms and larvae of cigarette beetle [*Lasioderma serricorne* F. (Coleoptera: Anobiidae)] and drugstore beetle [*Stegobium paniceum* (L.) (Coleoptera*:* Anobiidae)] feed on books, binding materials and dried plant parts. Their feeding results in burrows and holes in the infested materials. These damage patters can be used to identify these beetles when are present or absent in infested materials.

9) Cockroaches (Insecta: Blattodea) mostly feed on residues of molds and starchy/protenecious materials deposited on different surfaces including wodden/plastic furnitures, clothings, papers, cardboards etc. Their faeces and drooping cause staining of the mataerials. The female cockroaches adhere their egg pouches to any ptotected objects. Presence of egg-cases and stained materials can be used as indicators of their presence.

2.4. Understanding biology and ecology of pest: Theories and Practical

An efficient, effective and successful management of insect pests is always founded on a comprehensive knowledge of the biology, morphology, internal anatomy, behavior, growth (metamorphosis), life history and ecology of the insect pest. The morphological knowledge of an insect helps to develop an appropriate technology and decide the selection of appropriate insecticide. Chemotropism based techniques involving attractant or repellents have been developed for various insect pests. The development of such techniques depends upon knowledge about chemoreceptors like, gustatory, olfactory, sensory receptors etc. Development and selection of color of light of light-traps depend on the knowledge of structural components and physiology of compound eyes of insects (Dhaliwal and Arora 2003; Pedigo and Rice 2009). The knowledge of structural components and physiology of compound eyes of insect provide information about the type of color which is highly attractive for any insect. For example, yellow sticky traps are used for the control of aphids as aphids are attracted to yellow colour (Saha and Dhaliwal 2012). The knowledge about the types of mouthparts of insect pests helps to decide what type of insecticides should be selected for successful control of the insect pest. For example, if the infesting insect pests have sucking type of mouthparts, then, insecticides with systemic and contact action are the most appropriate. Unlikely, if the infesting insect pests have chewing type of mouthparts then stomach poisons will give effective control. Unawareness of the knowledge of the mouthparts of insect pests leads to wrong selection of insecticides and ineffective management of insect pest in spite of investment of money in form of insecticides application (Saha and Dhaliwal 2012).

Knowledge of internal anatomy and physiology is also very advantageous in devising pest management tactic. For example, so many insecticide molecules with IGR or karomone activity have been discovered and their analogs have been synthesized for commercialization and management of insect pests. These molecules are based on growth hormones, parasitoid's sting-glands peptides and hormones. The knowledge of spiracular respiration can be helpful in controlling the insect pests with fumigation (Hoffmann and Frodsham 1993).

The knowledge of insect metamorphosis and its physiology provides so many useful informations about the week links of insect growth stages and their activity periods and sites which if targeted can ensure for effective management of any pest. Such knowledge can also be useful in synchronizing the timing of application of pest management tactics with week-link or susceptible growth stage of insect; thus, ultimately would be helpful in reducing blind use and application intensity of pesticide on crop. This information would lay the foundation of decision on when, where and how to use available and recommended insecticides or other pest management tactics. Information on the metamorphic stages like, eggs, larvae/nymphs/naiads, pupae and adults of insects comprehend the facts that which stage is notorious, devastating and damaging one and which are not. This information also precises the damaging-stage-specific application of control measures.

Ecological Pest Management (EPM) is one of the key components of IPM. EPM emphasis on targeting many life stages of pest by pest control and minimizing its survival potential with least possible resources/ways (Schowalter 2011). These objectives of EPM can be achieved by following the ecological principles exactly in intimation with nature. It is imperative to devise a production system primarily on the pillars of solid and accurate information, multiple production and protection tactics and ecological principles. Such production system strengthens the individual and combined efficiency of the strategies being used, distribute the plant protection burden across multiple tacticses and minimizes the chances of complete crop failure. This system also reduces the blind, chain-repeated and frequent use of one tactice/strategy and resultantly it not only minimizes the rate of resistance development but also lessens its inputs rquirements, reduces operating cost and enhances its productivity and profitability (Pedigo and Rice 2009)

The study of the behavior of insects also laid the foundation of successful control of insect pests. Insect behavioral studies figure out following important facts of their life that can be helpful in controlling them.

2.4.1. Egg laying behavior

Some insects are endophytic (fruit flies) and some are exophytics (most of the bollworms and borers). Most of the insects deposit exposed eggs while some deposit the covered egg masses. Depending on egg laying behavior, pest management tactic is decided to control insect pest at egg stage.

2.4.2. Behavior of newly emerged young ones

The young ones of most of the borers just after hatching enter the leaf whorls or stem of the plants, avoid the direct exposure of insecticides and become very difficult to kill with contact insecticides. Similarly, leaf miners just after hatching enter the cortex tissues forming mines and cannot be controlled with contact insecticides. Young ones as well as later instar larvae of cutworm remain hidden in cracks and crevices and insecticides application direct on plants during day time will not yield effective control. Their effective management can be ensured if chemigation of insecticides or bait application is employed.

2.4.3. Feeding behavior in young ones

Feeding habit of insect pest also help in deciding the types of tactics and method of their application for effective management of any insect pest. The insect pest which prefer to feed underside the leaf can be controlled effectively by application of systemic and translamiar insecticides. Similarly, borers (Insecta: Lepidoptera and Coleoptera) exhibit concealed feeding inside the stem which cannot be killed with contact insecticides; rather systemic insecticides will be the most appropriate tactic for the management borers.

2.4.4. Breeding place

Nipping the evil in the bud for insect pests is possible only if their exact breeding sites are known. It is possible only through comprehensive studies of their biology. The breeding places of mosquitoes are stagnant water and their treatment with larvicides, ovicides or oils help in controlling the breakout of adult population. Cockroaches breed in filthy places which should be targeted with insecticides treatment for their management at bud/root level (breeding places) for terminating their further population buildup and outbreak. For fruit flies, the breeding substrates are dropped fruits which should be collected and destroyed for their population management.

2.5. Study of insect ecology and IPM

The study of insect ecology provides the conceptual and theoretical framework which offers the practical ground for the application of pest management discipline (Driesche et al. 2008). Interactive effects of insects and other organisms of the agroecosystem influence insect pests management strategy (Schowalter 2011). The solution of insect problems majorly depends on ecological management which is considered as one of the oldest, least expensive and ecologically the most compatible tactics. Ecological studies of insects help in identifying and exploiting the weak links of seasonal life cycle of insects. Such studies also help to explore the food and physical factors which impact insect's life negatively. By manipulating of such factors unfavorable for insect survival, insect pest's outbreak, population buildup and damage impacts can be avoided in an ecofriendly way (Pedigo and Rice 2009). Study of insect ecology also laid the foundation of plant-insect-predators/parasitoids interactions which help to frame out the pest management strategy for any insect pest. According to vegetable system defined by Joe Lewis and Steve Groff (Pattison 2005), a combination of tillage and mulching of vegetables with cover crops conserves sufficient biodiversity for pests. Such integrated practices result in conservation of field and increase beneficial insect populations fourteen times higher than in the conventional fields. A conducive and effective balance between pest and beneficial fauna can be sustained in the crop production system on a farm by maintaining propotionate undisturbed areas on it. The natural enemies (predators and parasites) attacking pests mostly survive, established and conserved in the undisturbed sites like hedges, weedy borders, grassed alleyways, woodlots, grassed waterways, riparian buffers, and small undisturbed areas maintained between rows of major crop. Such undisturbed areas support multiplication of natural enemies and their migratation into crops fot biological control of pest population. Conservation of diversity in agroecosystem based on ecological studies of insect life can reduce pest problems. Maintenance of diverse cropping at different growth stages and utilization of diversed multiple management tactics will results in suppression of pests under broad-ranged stresses. These types of broad-ranged stresses create difficulties for the pests to locate their favourable crop hosts as well as to develop resistance rapidly against adopted pest management measures (Schillhorn et al. 1997; Pattison 2005).

Insect ecological studies also help to select various alternate host plants which can serve as trap and cover crops. Such crops, when intercropped or border-cultivated, not only recruit entomophagous insects in their battle against insect pests on major crops but also create a nice habitat for feeding and overwintering of beneficial insects. Between his raspberry rows, dandelions flower serve as source of food for nectar- seeking and polliferous insects. Insect ecological studies also laid the foundation of insect chemical ecology that yielded the discovery of so many semiochemicals and their potential implementation in pest management program of so many insect pests (Pattison 2005). For example, discovery of pheromones (methyl eugenol for fruit flies and gossyplure for pink bollworm), allomones, kairomones and synomones are based on insect chemical ecology studies (Saha and Dhaliwal 2012).

2.6. Management of insect ecosystem: Structure to implementation

Ecosystem management influences the interaction of pests with other functional and structural components of ecosystem and determines the sustainability of pest management approaches. It is, therefore, imparative to understand the structure/components of the prevailing ecosystem (Schowalter 2011).

Physical structure of an ecosystem represents the size and distribution of its density-dependent (biotic) and density-independent (abiotic) components. These both types of components determine the types and intensity of application of pest management tactics/strategy. For example, an ecosystem having biotic and abiotic factor very severe for pest survival should be exhibited with do-nothing or at least with minimum anthropogenic pest management tactics. Unlikely, if the ecosystem is characterized by such biotic and abiotic factors which favour the pest outbreak and population growth, intensified pest management program/strategies become mandatory to avoid the losses by insect pest population (Trenberth 1999; Juang et al. 2007). The physical structure of an ecosystem also determines the prevailing insect species and their competitors, accordingly determine the nature of pest complex and ultimately help in selection of pest management program.

Another component of an ecosystem is the trophic structure which represent the numbers, mass (biomass), or energy content of organisms in each trophic level in form of numbers pyramids, biomass pyramids, or energy pyramids (Elton 1939). Trophic structure constitutes both herbivores and their predators as well parasites. The interaction of these herbivore and their natural enemies affect the complexity of herbivore and carnivore effects on ecosystem structure and function. If the trophic structures are favoring the herbivoric effects and limiting the carnivoric effects, then that trophic system support the implementation of pest management tactics. On the other hand, if the trophic structures are favoring the carnivoric effects and limiting the herbivoric effects, then that trophic system support the implementation of do-nothing strategy because predators, parasites and other natural fatal factors are actively contributing to regulate biological equilibrium (Schowalter 2011).

2.7. Pest management and economic decision levels: Decision staircase, concepts and practicality

The decision staircase of pest management program shows that successful and sustainable pest management depend on certain pillars of pest management tactics that basically stand on the foundation of six slabs (biology, ecology, threshold, models, sampling and taxonomy) and one of those is economic decision levels (thresholds). Economic decision levels (EDLs) are indispensible for devising and implementing insect pest management program in an effective and economical way (Pedigo and Rice 2009). The comprehensive and true practical knowledge of such decision levels ensure the sensible and timely use of insecticides because these levels highlight the exact density of insect population that may cause economic damage if insecticides are not used. Ignorance of these economic decision levels leads to ridiculous economic gaffes spending more cost on pest management and crop protection than benefits a pest management strategy/tactics may ensure. A comprehensive and proper knowledge, understanding and use of these economic decision levels can enhance the profit ratio of the growers and ensure the conservation of the environment and biodiversity (Dhaliwal et al. 2006; Pedigo and Rice 2009). Briefly, proper and sensible utilization of EDLs has following plus-points (Knipling 1979; Pedigo and Rice 2009):

1) Sensible use of insecticides and avoidance from the indiscriminate use of insecticides
2) Reduction in insecticides use
3) Increase producer's profit ratio
4) Conserve natural biodiversity

5) Conserve the environment quality
6) Solution of some functional, biological and environmental issues like food-safty and food-security, development of ecological-backlash in form of 3Rs (Resistance, Resurgence and Replacement) and negative impacts on environment, human and various non-target organisms.

These EDLs include EIL (Economic Injury Level), ETL (Economic Threshold Level), GT (Gain Threshold) and DB (Damage Boundary). Among these, ETL is the practical operational level which is recommended to and being practiced by the growers for making pest management decisions in many situations. ETL is mostly used for making decision about the strategic implementation of curative/therapeutic management tactics including mainly insecticides. The use of ETL in pest management programs depend on following four decision rules (Knipling 1979):

2.7.1. No-threshold rule

No-threshold rule is applied when: i) sampling and scouting is uneconomical; ii) timely and practical implementation of remedy measures for the problem is difficult; iii) timely remedy and treatment of the problem is impractical; iv) too low ETL of pest; v) threats of quality losses, outbreak and transmission of fatal disease, too quick growth potential of pest/disease are confirmed); and vi) general equilibrium position of the pest always remains intensively above EIL.

2.7.2. Nominal threshold rule

This rule is established on the bais of skills, expertise and experiences of the entomologists. It is the most widely and frequently used economic threshold rule in any pest management program. An expert and professional entomologist defines ETLs for the prevailing pests based on his longlife field experiences.

2.7.3. Simple threshold rule

According to this rule, field experiments are conducted under controlled conditions for various infestation levels of a pest to determine its ETL. The ETL is calculated based on various parameters like market values of the commodity, cost of pest management practice, damage/loss done by specific pest density or pest infestation level and yield as well as monetary loss reduced by pest management practice on per plant or unit area basis. The ETLs calculated in this way are used in pest management.

2.7.4. Comprehensive threshold rule

This rule implies the ecological/environmental threshold levels. The determination and calculation of such economic threshold involves all possible interactive impacts of different biotic and abiotic stresses on tritrophic cascade of pest, plant and natural enemies. Calculattion and implementation of this comprehensive threshold is possible only if on-farm GPS and GIS based information collection and delivery setup is available.

2.8. Pest monitoring and scouting

2.8.1. Pest monitoring

Monitoring phytophagous insect pest and their natural enemies is the fundamental tool in IPM for making management decision (Dhaliwal and Arora 2003). Monitoring highlights the fluctuation in distribution and abundance of insect pests, outbreak and life history of insect pests and influence of biotic and abiotic factors on pest population. Monitoring helps in detection of outbreak of indigenous and exotic insect pest species, understanding ecological, climatological and biological factors regulating the pest movements, determining emergence pattern and generation peaks of important insect pests and detecting the rate of development of insecticide resistance in important insect pests. All these monitoring oriented information help to develop predictive models which are used to forewarn the growers regarding insect pest's outbreak and to develop and use sampling schemes as well as initiate management strategies (Dhaliwal and Arora 2003). Monitoring also provides following important information:

- Kind and category of pests prevailing the crop
- Density of the pest
- Whether the prevailing pest density demands control measures?
- Have the implemented pest management practices suppressed the pest population significantly?

Various sampling tools including absolute estimate, relative estimate and population indices are used for monitoring insect pests. Various techniques which can be used in monitoring programs of various insect include *in-situ* counts, knockdown (jarring, shaking, beating, heating or chemical knockdown), netting, trapping (light traps, pheromone traps, pit-fall trap, Malaise trap, sticky traps), extraction from soil by sieving, washing, floatation, berlese funnels and soil-sampler (Pedigo and Rice 2009; Saha and Dhaliwal 2012).

2.8.2. Pest scouting

Pest scouting is the inspection of a field to determine crop condition, severity of pests and their losses and density of beneficial fauna in a specific crop using already well defined and established pest-scouting methods/techniques. The philosophy and principles of pest control stress on the management of a pest only when its incidence is causing or is expected to cause damage above the acceptable/tolerable limit. The philosophy of pest management also emphasizes on the implementation of a pest management strategy which ensures a significant reduction in pest density to a tolerable level and encourages the conservation of non-target fauna of an agroecosystem (Dhaliwal and Arora 2003). Sustainably successful, effective and economical pest management program is always based on some important informations including: 1) which type of pest is prevailing in the system (pest identification), 2) What is the pest density per unit area? (ETL), 3) whether the pest density/population is increasing or decreasing (pest dynamics), 4) when the pest is present (pest activity period) and 5) How much damage the crop can tolerate (Host plant resistance). These informations can be obtained by implementing regular pest scouting program in the crop during crop season. An efficacious and successful integrated pest management (IPM) program absolutely depends on accurate identification of insect-pest. A correct identification of any insect pest can be accomplished by conducting regular pest-scouting. This practice, if performed accurately, helps in early prediction of pest outbreak, selection of appropriate control measures from the available widest range of pest management options and bringing satisfactory socio-economical and ecological, benefits (Schillhorn et al. 1997; Rondon et al. 2008). A successful pest scouting program depends on accurate history and record-keeping of conditions and locations of farm, pest incidence, pest mapping and pesticides usage. These secords facilitate the farm-managers or growers in anticipating crop conditions, diagnosing epidemic or endemic pest problems and tracking each field of the farm. Pest scouting helps in identifying the pest(s) problem(s), determining the exact site of pest problem, deciding either control is needed or not, selecting true insecticides, knowing the types of available control measure, determining and selecting more appropriate, effective and economical control measure, evaluating the evidences of effectiveness of control measures used and assessing their risks and benefits. It also demonstrate pest population trends, crop conditions, insect growth stages, current weather conditions, to-date degree of damage to crop, crop growth stage, expected yield, other pest problems, activity and incidence of natural enemies, prevailing economic decision levels of key pest and success of already use pest management measures All these informations help in understanding population dynamics of insect pests and their potential impacts on yield and cost-benefit-ratio (CBR), determining the either the pest management measures should be adopted or not?, selection of the types of control measure that is needed to prevent economic losses. Pest scouting determines either pest population is above or below ETL or insecticides should be used or not (Rondon et al. 2008; Omafra 2009; Jha 2010).

Timing of pest scouting is also very crucial principle which ensures the successful and result-oriented pest scouting program and ultimately guarantees the success of pest management strategy. Time of pest scouting vary from crop to crop, insect pest species to species, plant growth-stage to growth-stage and locality to locality. Prompt identification of existing pests and appropriate selection as well as timely application of pest control strategies can minimize economic impacts of pests on any crop. Crop scouting calendars based on previous records and data illustrate the timing of scouting associated with crop and insect-pests found in any specific locality. Consistent and frequent monitoring and scouting is very imperative because insect-pest dynamics keep on fluctuating quickly and frequently throughout cropping season. Optimum plant populations are very critical for obtaining good yield; that's why crops scouting should be initiated within 1-2 weeks of plant emergence. Weekly scouting is appropriate early in the growing season. However, when insect pest population is approaching a control threshold, fields may require scouting daily; while, bi-weekly scouting is normally sufficient later in the season. For those insect pests which appear later in the season (like armyworms, aphids etc.) and may approach control thresholds in a matter of days when field and weather conditions favour these later-season pests, scouting should be continued weekly (Rondon et al. 2008; Omafra 2009).

The crucial factors that laid down the foundation of accurate and successful pest scouting program include number of sampling and sampling patterns. The foundation of correct and accurate scouting program as well as of the collected data is laid on the appropriate number of sampling locations in a field that ultimately depends on field size, crop, pest type and stage of development, level of infestation, timing, etc. (Omafra 2009). Generally, the number of the recommended sampling locations for scouting insect-pests based on field size are 5, 8 and 10 locations for up to 8 (20 acres), 8-12 (20-30 acres) and 12-16 (30-40 acres) hectares, respectively. However, the fields larger than 16 ha (40 acres) should be split into units of 16 ha (40 acres) or less for insect pest scouting. Scouting pattern is also very important for accurate pest scouting of any insect pest. Use a scouting pattern that address all plant-growth-regulating factors including changes in variety/hybrid, soil type, past cropping history, fertilizer/manure application insect pest etc. (Rondon et al. 2008). Following information and criteria should be considered for determining the type of scouting pattern:

- The pest-scouting pattern should cover whole of the field areas andlocation for observation should be different for each time the field is scouted. However, already scouted locations/fields should be rechecked to monitor the latest situation of pest development when hot spots are recognized in crop production system. For the insect pests, which are uniformly distributed across the field [like, corn borers (Insecta: Lepidoptera; Pyralidae), rice and sugarcane borers (Insecta: Lepidoptera), bollworms (Insecta: Lepidoptera), jassids (Insecta: Homoptera; Cicadellidae), whiteflies (Insecta: Homoptera; Aleyrodidae) etc.], select sampling locations randomly and evenly from whole the field and start pest-scouting leaving field border area of at least 20 m (66 ft) width. Principally, avoid pest-scouting in headlands or from some surrounding rows at field edges and always practice the scouting evenly throughout the field.
- For insect pests expected to develop in headlands or outside rows, select sampling locations randomly and uniformly at the boundaries of field and perform pest-scouting preferable around the edges of the field.
- For insect pests, which usually develop in a particular field areas, sampling locations should be selected and pest-scouting should be concentrated on those specific locations. However, other areas of affected fields should also be scouted.

Lack of pest monitoring and scouting in the crops results in incorrect pest identification, inappropriate selection of pesticide, its dosage, application method and rapid development resistant in insect pest against insecticides (Dhaliwal et al. 2006; Pedigo and Rice 2009).

2.9. Selection of control practices: principles and criteria

Selection of an appropriate control practice or highly compatible control measures is a key to success of any pest management program. Following principles and criteria should be kept in mind while selecting single or set of control practices;

2.9.1. Feasibility in available resources

The selected control practice(s) should be feasible under resources available at farms. Principally, the availability of managerial time, adequate work-force/labor, as well as of appropriate and functional equipments, required for undertaking any particular pest management practice(s), should be predetermined. The availability or accessibility of above-mentioned farm resources are perhaps the major constraints in implementing prticular pest management strategies (Schillhorn et al. 1997)

2.9.2. Flexibility in cropping program

Before selecting control practice(s), it should be determined whether the cropping system under discussion has sufficient flexibility to respond and tolerate pests under the influence of specific pest control practice(s) (Knipling 1979; Inayatullah 1995).

2.9.3. Economic feasibility

The economic feasibility of the pest management practice(s) should be estimated and compared. After the establishment of economic thresholds for many pests in the field, there is no hard and fast economical pest control decision rule for the selection of one or many pest control strategies. As a rule, economic feasibility can be determined on some economic basis. First, the expected benefits of a given pest management practice(s) should be considered and if the expected costs exceed over time, the pest management practice(s) should not be adopted. If several pest management practices have estimated benefits/returns higher than their expected costs, then select only those which prove economically and operationally more efficient and sustainable in crop production system. If more than one falls into this category, select the one with the greatest expected return. Costs of a pest management practice(s) include the value of any special equipment and machinery, work-force, pest-management inputs and managerial time/services needed (Knipling 1979; Schillhorn et al. 1997).

2.10. Goals of pest management

Pest management measures should address the principle goals IPM program. The main goals of any pest control program/strategy include prevention (hinder pest outbreak from getting epidemic form), suppression (reducing density and/or damage of pest to a tolerable level) and eradication (complete destruction of pest) (Kogan 1988; Farrell 1990; Pedigo and Rice 2009).

Prevention may be a goal of any pest management program/strategy when the incidence or abundance of any pest is foreseeable and predictable in advance. For example, for management of mosquito, house flies, household insect pests, locust swarm etc. prevention is the best principle goals for successful suppression and control of pest population (Knipling 1979).

Suppression is a common goal of any pest management program/strategy in many pest situations. The philosophy of this specific goal is to supress pest density and minimize the pest damage to tolerable and acceptable level. This goal addresses the philosophy of the holistic concept of IPM program (Schillhorn et al. 1997; SP-IPM 2008).

Eradication is a common goal of any pest management program/strategy for in indoor areas and for those insect pests which infest food commodities or act as carriers/vectors of animal diseases where loss of single food-grain/commodity or life is not bearable. In indoor and closed areas, the achievement of this goal by any pest management program is comparatively easier than outdoor and opened areas because enclosed environment is comparatively less complex and easier to manage than outdoor areas/environment. For example, the prime goal of pest management program will be eradication of insect pests inside enclosed areas, like apartments, teaching institutions (schools, universities, colleges etc., offices, industrial units` because the incidence of certain pests and their losses cannot be tolerated there and zero-tolerance is set as basic principle and goal of pest management program (Schillhorn et al. 1997; Pedigo and Rice 2009).

2.10.1. Ecological backlashes: Causes and management

An effective pest management tactic suddenly loose its effectiveness or becomes totally ineffective. The failure of any pest management tactic suddenly or with the passage of time may be due to selection of inappropriate and incompatible tactics and improper application technique. However, if appropriate and compatible tactics are used with proper technique even then pest management tactic may face failure which is due the counter responses exhibited by the insect species against the stress imposed by that pest management tactic. Such counter responses are called ecological backlash which consist of three major sources of this phenomenon. These three sources include "three Rs" i.e., resistance, resurgence and replacement. An understanding of the philosophies of these sources of ecological backlashes also helps to make some decision on the use of any pest management tactic/strategy. If the pest management measure is facing the problem of ecological backlash, then use of more than one control measures is appropriate for delaying ecological backlash. For selection of appropriate pest management tactics/strategy, the need is to understand and have comprehensive knowledge of all the factors which influence the rate of development of ecological backlash in insects. These factors are categorized into operation and biological factors. The operational factors include the prolonged exposure of insect population to control tactic, selection pressure on every generation of insect pest, very high selection pressure of control tactic, absence of functional refuges, coverage on large geographical area, continuous application of insecticides with same mode of action and setting of very low population threshold. Biological factors include exhibition of no or little migratory behavior by inset population, monophagous nature of feeding of pest population, short generation time of insect species and very high natality of insect species. The techniques which can slowdown the rate of development of ecological backlash include: 1) reducing selection pressure and conserve susceptible gene pool in population by moderation technique; 2) saturating insect defense mechanisms by doses of pest management tactic that can overcome the ecological backlash; 3) reducing the selection pressure by adopting multiple attacking system/approach (Knipling 1979; Pedigo and Rice 2009).

2.11. Development and implementation of IPM strategy

After the reception of any pest management containing both preventive and therapeutic practices, there is need to develop IPM strategy which depends on the principle of combining tactics. For the development of IPM strategy, first identify potential preventive and therapeutic measures, evaluate the tactics individually, formulate conceptual plan of potential system, conduct field trials with the system to determine costs, compatibility of the tactics, effectiveness of the system and deploy successful program that offer on-farm flexibility (Schillhorn et al. 1997; Pedigo and Rice 2009). Other than these, there are also so many other steps and procedures that should be adopted to develop an IPM program/strategy having high success and sustainability rate. The step-by-step procedures for developing an IPM program/strategy are given below (Norris et al. 2002; Pedigo and Rice 2009):

- Identify all insect pests, their life stages as well as their natural enemies in the system.
- Establish first crude and then refines as well as improved monitoring and pest scouting guidelines
- Establish injury levels and action threshold for each pest species in the system
- Establish a record keeping system for evaluating and improving any IPM program
- Develop a list of acceptable management strategies for each pest preferably the preventive strategies and then therapeutic strategies.
- Develop a specific criterion for the selection of pest management methods like; i) least destructive to natural control and beneficial fauna, least hazardous to human health, least toxic to non-target organisms, exhibit sustainable reduction of pest population, easy to carryout in the system and most cost-effective in the short- and long-term situation.
- Develop guidelines for the selection of pesticide every time.
- Evaluate the sustainability of the IPM program

After the development of IPM program, next step is to determine its implementing protocol which will ensure the removal of all the barriers expected to destroy the philosophy of IPM program. Following are some suggestions which help in overcoming the barriers and smooth implementation of IPM program (SP-IPM 2008; Pedigo and Rice 2009).

- Always initiate the IPM program on small scale as well as on one place addressing predetermines short-term objectives
- Do not change everything at once; rather retain to the maximum degree all the procedures already in use.
- Share the IPM program with all the management personnels involved in day-to-day IPM process as soon as possible so that they can understand and support the program.
- Keep all the personnels informed about what is being planned, what is happening now, the expected outcomes and what will happen next.
- Identify benchmark objectives of IPM program and then build an reward system for the recognition of the personnels who are adopting IPM program in well manner
- Publicize the IPM program through field staff, personnels, communication media and interview session, website development.
- Involve the community by developing an advisory committee composed of interested IPM personnels and organizations.

2.12. Factors causing failure of pest management strategies

The sustainability of any pest management strategy depends on exploring the causes of its failure rather than rejecting it at once. Following are the main causes of the failure of pest management strategy (Schillhorn et al. 1997):

- **Incorrect identification of insect pest species:** It results in wrong selection of control measures and failure of whole pest management strategy.
- **Selection of inappropriate control measures:** It poses negative impacts on non-target beneficial organism but does not ensure the suppression of the target insect species. and failure of whole pest management strategy.
- **Selection of incompatible control measures:** This cause reduces the efficacy of the selected control measures due to their antagonistic effects on the control potentials/properties of each other and ultimately the designed strategy face failure.
- **Selection of inappropriate application technique:** Sometimes the control measures are very strong and effective but their application techniques reduce the effectiveness of the control measures and failure of the pest management strategy.
- **Improper timing of application of control measures:** If very effective control measures are not applied at the correct time, it also leads toward the

failure of the strategy. For example, application of chemical control during the unfavorable climatic conditions- when there is expectation of rain or windstorm, application at noon etc. - will either yield no control or least control of the target insect pest species.

- **Application of same tactics excessively:** This practice results in rapid development of resistance in insect pests against pest management measures and ultimately causes prompt reduction in the effectiveness of the pest management strategy.
- **Development of resistance in insect pest species against control measures:** Development of resistance against control measure due to its excessive and blind use is the critical and vital factor which causes the failure of any pest management strategy.
- **Adverse climatic conditions:** Sometimes climatic conditions, which are adverse for the performance of pest management strategy and favor the pest population growth, prove a big hurdle in the implementation pest management strategy, reduce its effectiveness and sometime result in its failure.
- **Use of incorrect dosage of pest control measure:** Pest control measure, specifically chemical and biological control do not perform effectively if they are not applied at their recommended and effective dosages even though they are implemented with strong and productive strategy. Use of incorrect (under dose or over dose) dosage either results in futility of pest management strategy (in case of under dose application) or rapid development of resistance (in case of over-dose application) in insect pests against control strategy (FAO 2014).

2.13. Public awareness, long-term commitment, planning and improvement: Procedures and strategies

Success of any strategy and plan depends upon its adaptability to the public sector. A consistent and sustainable application of any pest management strategy is very important to get the desired results. The sustainability of any pest management program/strategy vitally relies on public awareness, long-term commitment of the involved personnels and planning as well as improvement in the existing pest management program. Most important step which ensures the sustainability of any pest management is awaring and demonstrating public with advantages and application strategies of introduced and developed pest management program so that they can implement it in strategically accurate and economically effective way (Metcalf and Luckmann 1975; Flint and Bosch 1981; Kogan 1988). There are different procedures or method which can be used for the public awareness about the pest management program. These methods include public awareness campaigns through paper and electronic media, involvement of various NGOs and farmer’s field school (FFS) working at the grass-root levels of the farming community, organizing training workshops, symposia, conferences etc., and field demonstration of the technology. Creating public/stakeholder awareness is not enough guarantee for the long-term sustainability of the transferred pest management technology (Flint et al. 2003). Every stakeholder should be committed to follow all the awareness-campaign-highlighted pre-requisites which ensure the sustainability in the effectiveness of pest management program/strategy. If the IPM personnels/stakeholders do not remain committed to follow the pre-requisite of sustainability of IPM program in the long-run, the IPM program will reduce its effectiveness and sustainability sooner or later. The IPM personnels/stakeholders of any specific area, locality or region must committedly consider, implement and monitor calendar, methods and tactics, strategies and emerging flaw/issues of implemented IPM program. Then another aspect of sustainable program includes planning to diagnose the cause of emerging issues and address their possible solutions for the improvement and long-term sustainability of already existing IPM program in the scenario of evolving pest issues and new technologies rather exploring and designing new pest management program (Flint et al. 2003; Dhaliwal et al. 2006).

2.14. General principles of chemical and biopesticides

All pesticides, being poisonous substances, can impose detriment effects on all living things; that's why, they must be used in a judicious way. The selected techniques for insecticide application should ideally be target oriented so that the non-target organisms as well as the environment can be protected from the lethal residual and deteriorating impacts of insecticides (Grant et al. 2003; Van-der-Wulp and Pretty 2005; Jha 2010). Additionally, comprehensive information of the equipment used for insecticide application is also very indispensible for: 1) the development of an anticipated dexterity of operations; 2) the selection and approximation of the number and kind of equipments for the optimized used of the selected equipment and accurate coverage of the crop in least spell of time (Omafra 2009; Pedigo and Rice 2009).

For the successful implementation of insecticide based pest control program, comprehensive knowledge of application technique, target, application time, coverage requirement, droplet size, calibration requirement, precautionary measures for handling, agitation and mixing requirement and equipment and tools used are required. The determination of all knowledge based on knowledge of pest problem, insecticides, formulations, technique and equipment (Knipling 1979; Matthews 2000). The knowledge of pest problem tells: 1) location of the pest-insect that helps in defining the target; 2) the most susceptible stage that aids to decide the time of insecticide application; and mobility/dispersal behavior of the pest that helps to define coverage and droplet-size requirement. The knowledge of the insecticides states: 1) their mode of action that define the application technique required; 2) their degree of phytotoxicity that define their calibration requirement; and their mammalian toxicity that determines the precautionary requirements for handling insecticides. The knowledge of insecticide formulations tells: 1) the type of solubility that defines the agitation requirements of the insecticides; and 2) the methodology of their mixing with water or other solvent for tank-mixing that determine the suitable measures and tools required. The knowledge of techniques and equipments states: 1) the procedures/methods and protocols for their operation and maintenance so that they can be operated in the field without any field difficulties; 2) their capabilities that help to estimate the number of equipment needed; and the type of technique that should be selected and this information help to select the suitable and most appropriate equipments (Trivedi 2002; Sorby et al. 2005; Alam 2010). The various factors or principles which determine the success or failure of pest control by insecticides are discussed below:

2.14.1. Selection of suitable application technique

There are various techniques which are used for application of pesticides. The formulations of insecticides are made available in liquid, dust-powder, granule or slow-releasing forms which ensure their application in small quantities over large area. Application of insecticides in small recommended quantity is possible only if proper application technique is adopted. Therefore, selection and adoption of the most appropriate technique and equipment for pesticide application are very vital for depositing insecticides uniformly, performing pest control operation accurately and getting the effective results from any pesticides. The selection of pesticide application technique depends on the type, life-stage and feeding as well migratory behavior of the insect pest, site/substrate to be treated (on foliage, under the leaves, at root zone, plant whorl, breeding places etc), types of insecticide formulation, etc (Metthews 1979). For examples, granular insecticides against borers are applied by whorl application or by chemigation techniques but their foliar application will not yield the effective results. The most appropriate technique for the indoor control of mosquito is the use of chemicals in form slow-releasing or fogging technique. Effective monitoring and control of fruit flies is possible by pheromones when these are applied by trapping and insecticide coadministration technique. Similarly, for the control of eggs and young ones of mosquito and cockroach, the most appropriate technique is the breeding-site-treatment method for insecticide application. For cutworm control the most appropriate technique for the application of insecticides will the food-bait or chemigation technique. In short, it is the principle, while using insecticide, that the most appropriate technique should be used otherwise, the required results will not be achieved.

2.14.2. Selection of appropriate and quality insecticides

Various types of insecticides like OPs, OCs, pyrethroids, carbamates, IGRs, neonecotenoids, biorationals and many others with novel mode of actions are used for the management of different insect pests, obtaining quality yield and reducing yield losses. But selection of an appropriate insecticide of standard quality (i.e., proper quantity of fresh not expired active ingredient with standard and good quality inert material in proper proportion as described on label) is first principle that will assure the success of insecticide based pest control program (Matthews 2000; Food and Agriculture Organization 2014).

2.14.3. Decision on the timing of application

After selection of an appropriate insecticide of standard quality, decision on the appropriate application timing is the next principle that can lay down the base of successful pest control program. Application of insecticide is very efficacious and yields the required result if applied at the most susceptible stage of the pest. The timing of insecticide application should prudently be considered and followed for good and economical results (Matthews 2000; Pedigo and Rice 2009).

2.14.4. Proper application of insecticides

Application of good quality insecticide at ideal timing does not yield good and economical results until or unless it is applied properly and qualitatively. The proper and quality application of insecticides is an imperative principle of pest control program. The proper and quality application of insecticides can be achieved if proper dosage is applied evenly, toxicant reaches the target, proper droplet size of insecticide is produces and sprayed and proper density of droplets is deposited on the target (Matthews 2000; Pedigo and Rice 2009).

2.14.5. Application of proper and recommended dosage

Every insecticide has its recommended dosage which is considered lethal for targeted insect pests but safe and non-phytotoxic for plants. The recommended dosage of selected insecticides should carefully be considered and applied to get good results. Over-dosage and under dose should be avoided because such practices do not yield the required results rather impose many destructive, hazardous and undesired impacts like, ecological backlash, environmental deterioration, phytotoxicity, health hazardous, deterioration of biodiversity etc. (Alam 2010; Jha 2010; FAO 2014).

2.14.6. Selection of the most appropriate equipment and associated tools/materials

Insecticides are applied by different methods including foliar-application/spraying, dusting, drenching, fogging etc. Depending upon the application method recommend for the selected insecticides, the most appropriate equipment and associated tools especially nozzles should be selected for getting good and economical results. Improper selection of equipments and nozzles results in poor and uneconomical control of insect pests. Different equipments which are used for insecticides application include hydraulic, centrifugal and gaseous energy sprayers, aerosols sprayers, dispensers, foggers, dusting equipments, granular applicators etc. Similarly, various types of nozzles like hydraulic energy nozzles (hollow-cone, fan/flat-fan and impact/deflector/floodjet, adjustable/triple-action nozzles), thermal energy nozzles, gaseous energy nozzles, centrifugal nozzles etc. are used for pesticides application. For tank-mixing before spray different solvents like water, oils etc. are used. The proper selection of spraying equipment and type of nozzle is very vital for achieving good coverage and accurate droplet size and ultimately successful and economical control program (Matthews 2000; FAO 2014).

2.14.7. Compatible and synergistic

Selection of insecticides which don't have any antagonistic; rather have synergistic interaction with other insecticides ensure the success of multiple-attack-system. Therefore, those insecticides should be selected for multiple-attack-system that are compatible with each other and synergize the toxic effects of each other. The selection and application of insecticides having antagonistic effects on each other result in the failure of multiple-attack-system. The selected insecticides should also be compatible with control measures other than insecticides or they should be manipulated in such way as reducing the side effects on other control measures (Joshi 2006; FAO 2014).

2.15. Conclusion

Pest management is an integral and vital component of manipulating, managing and regulating natural resources and agricultural systems. An area-wide public awareness campaign about the emerging pest issue must be organized and comprehensive knowledge of pests must be outreached to transform the aptitude, enhance the capacity and motivate the willingness of individuals to manage pests. An effective pest management entails a long-term and enduring commitment to pest management or pest eradication program by the industry groups, government entities, society and community. Discussion, meetings, consultation, entrepreneurship and partnership arrangements between industry groups, civic and rural communities, local governments and state government agencies must be established to attain a concerted, corporative and collaborative approach and strategy to pest management. Pest management or pest eradication planning, as per status of the emerging pest, must be reliable, consistent and sustainable at local, regional, state and national levels and must guarantee resources target urgencies, priorities and primacies for pest management recognized at each level. Preventative and anticipatory pest management is accomplished by early detection of the pest outbreak, local, regional, state and national level inhibition of pest migration, dispersal and spread as well as by intervention measures and strategies to control pests. Pest management must also be based on integration of highly compatible as well as ecologically and socially responsible therapeutic pest management practices and strategies that ensure environmental protection, food security, productive capacity of natural resources and conservation of natural resources as well as diversity. Fundamental and applied research about emerging or major/key pests and consistence, systematic and regular monitoring and evaluation of pest control activities is essential and indispensable to improve pest management practices for their better sustainability in any pest management program and system.

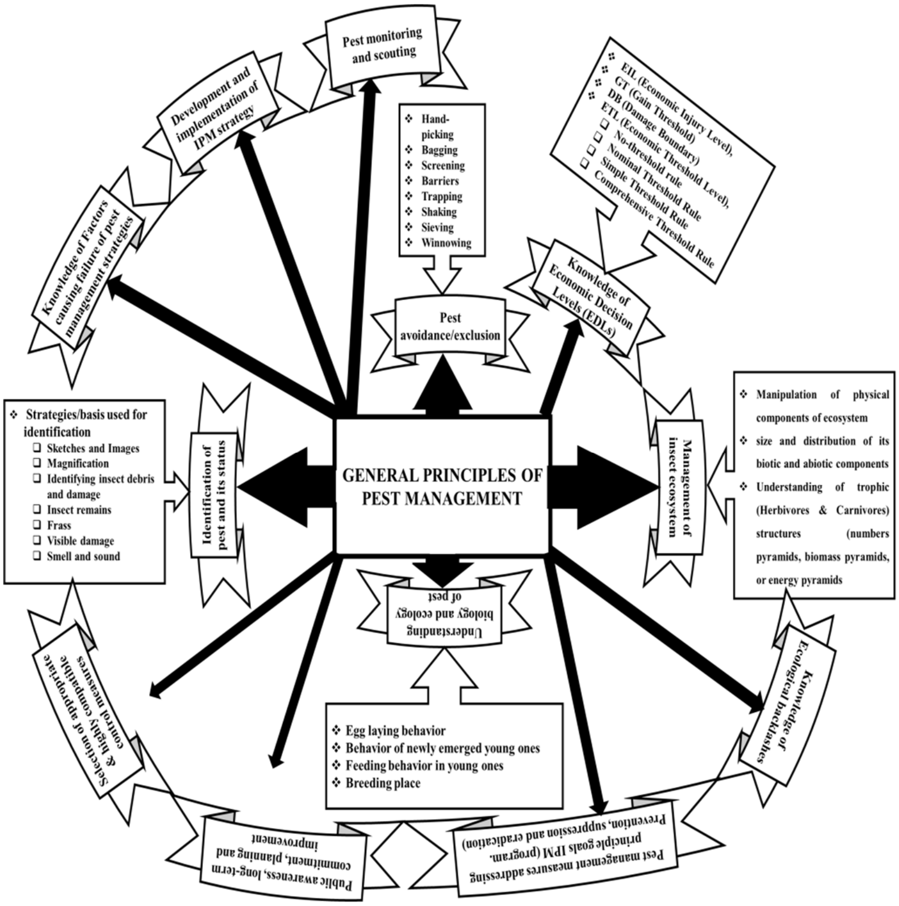

Fig. 2.3. General Principles which lay down the foundation of successful and sustainable pest management.

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Chapter 3

Insect-Plant Interaction: A Roadmap to Sustainable Pest Management

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Abstract

The phenomenon of insect-plant interaction is continued since the beginning of lives on earth. The communication between these two categories of organisms is complex and its consistent exploration discloses new and interesting aspects about it. The chapter deals with the various categories of tritrophic interactions between plants, insects and their natural enemies and provides an insight of these relationships. The active communication between different species (plants and insects) exists through secondary compounds released by the plants, however; members of the same species

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communicate through the signals and cues released by the other member (either insects or plants). The communication between intra or inter species because of coevolution develops various kind of resistance wihin the communicating organisms. The mechanism of resistance consists of antibiosis, antixenosis and tolerance. The deep understanding of these semiochemicals, connections and mechanisms between the members of an ecosystem can be exploited to maintain a balance in populations of insect pests and their natural enemies. Sustainable pest management can be efficiently applied by using natural resources and adapting innate traits in breeding programs to maintain the required characteristics in valued crops in agriculture.

Keywords: Insect plant interaction, tritrophic interaction, natural enemies, resistance, insect pests, sustainable pest management, tolerance, antibiosis, antixenosis.

3.1. Evolution and coevolution

The green plants along with their dependents i.e. herbivores have been coevolved since ancient times. Both have developed strategies to overcome the defense of each other and at time, one of these may drive extra benefit than the other. Evolution of plants started from the simplest unicellular form in mid-Paleozoic era, about 480 to 360 million years ago (Kenrick and Crane 1997a). This evolution continued and a wide range of flora has been evolved (Kenrick and Crane 1997b). With the evolution of plant life, the animal life started on the surface of earth and the first terrestrial animal form was reported 450 million years ago (Pisani et al. 2004) followed by the historic association of animals and plants on the earth. The coevolution of plants and animals is continued earth and both are overcoming the defensive traits of each other. The current chapter mainly focuses on the coevolution of plants and insects.

3.2. Insect-plant Interaction

The insect plant interaction is an important constituent of environmental balance on the earth. Their process of coevolution is continued since the beginning of the earth and becoming complex with the passage of time. New races, stains and biotypes have been evolved because of this complex association. Various components are playing a key role in this complex of insect plant interaction leading to various guild types in the ecosystems.

3.2.1. Components of insect-plant interaction

3.2.1.1. Host plants

The plants are one of the important components of insect-plant interactions. Both morphological as well as physiological aspects of a plant stimulate the reaction of the insects. The morphological features of the host plant are mainly responsible for insect attraction. Degree of foliage acceptance and its utilization by insects is totally dependent on the variations in physical conditions of host plants including; size, shape, color and release of various hormonal secretions. e.g., presence of hairy structures (pubescence) and hard leaf tissues often present the insect movement and feeding on the specific host plants.

Similarly, physiological characteristics of plants are responsible for the production of repellent chemicals against the insects. The secondary metabolic processes that are responsible for the production of these chemicals, termed as semiochemicals.

Primary and secondary plant metabolites often seem to be interconnected about their production in plants. The secondary metabolites or chemicals extensively produce in plants and are considered nonessential for primary metabolic processes. However, most of these secondary chemicals take part in the defense mechanisms of plants against herbivores. These metabolites are produced and stored in various plant parts and are secreted from external plant surface.

The release of these secondary compounds depends upon the feeding of herbivores on the target plants. The interaction between chemical response of plants and the insect feeding are of two types. The type of interaction existed among the members of one species is called "pheromones", however, the interactions among the organisms of different species is called "allelochemicals".

Allelochemicals are further subdivided into "Allomones and kairomones". The defensive elements which cause repulsion in insect behavior against their host plants are known as allomones, for example, repellent, oviposition and feeding deterrents along with toxicants are the allomones reported from plant systems. The chemicals which are responsible to increase connectivity between host and herbivores are considered as kairomones. Attractants and arrestants in plant systems are general examples of kairomones.

Host-plant selection by insects usually involves both primary and secondary substances (Plant products). Some theories emphasize and considered secondary metabolites as a main role; however, many pointed out that both play an important role. Host-plant odor or taste for insects comes from nutrients and secondary compounds that are combined to form a complex sensorial input. These inputs are initiated and control by insect central nervous system to determine a given plant as a host. In breeding programs for plant resistance, it is important to understand the nature of insect/plant relationships and their expression in host selection. Such understanding helps to exploit and generate the susceptibility in target plant species and enhances efficient development of resistant cultivars.

3.2.1.2. Insect herbivores

Insect herbivores are important constituents of insect plant interaction. Various areas of plant canopy are preferred by insects under the influence of certain physical factors, for example; light, gravity, wind, humidity and temperature. These physical factors play very important role for general habitat selection by insects. These factors are considered the important elements for habitat selection especially for migrant species and intruders.

The other most important requirement is to find the appropriate host plant in the suitable habitat. Sensory receptors particularly visual and olfactory help to sense and response towards host plants in a certain locality. However, the physical factors of the host plants including color, size and shape also responsible for attraction of insects, for example; sucking insects including most of the aphids and whiteflies find their host based on color and are attracted mostly to yellow-green surfaces (Bottrell et al. 1998). Normally, color is due to physiological characteristics and cannot be a part of plant resistance. Red cultivars of cabbage, cotton and oat hold less attraction to insects and can be considered as a good agronomic trait. Some fruit flies, *Ragoletis* spp. locate their host based on shape and size. In these conditions, short range stimuli are responsible for insect's movement towards their host plants. These stimuli can either be of physical or chemical nature.

After finding the proper host, insects take a test bite from it. Some caterpillars take sample bite on the host and decide finally to adopt the plant as a host or not. In monophagous herbivores, for example the silkworm (*Bombyx mori* L.), a series of chemical compositions of their mulberry host help them to continue swallowing and feeding. Major physical factors, for example; leaf structure, plant toughness, pubescence type and densities are involved in acceptance or rejection of a host by a herbivore. These factors play a role in feeding and oviposition of an arthropod on selected hosts.

Finally, the availability of sufficient quantity of nutrients from a host plant prove it as an appropriate host plant. Availability of adequate food without any toxin and threat for the feeding insect, help them to complete their normal developmental period with full potential of longevity and fecundity.

3.2.2. Types of insect-plant interaction

Different ways are used to classify insect-plant interactions. According to Southwood (1973), there are three main categories of basic interaction; exchange of food, shelter and communication between the insect and plant. Gilbert (1979) identified seven different types of interactions based on ecological relationship (Table No. 1). However, litreature review in case of phytophagous insects, points three important classes of interactions:

1) Insects act as predators
2) Insects act as parasites
3) Insects act as mutualists with host plants

Sustainable pest management strategies generally deal with first two categories (predators and parasites) and rarely with the third category (mutualists).

3.2.2.1. Insects as predators and phytophagous

Insect feeding and predation on host plants depend upon various factors such as various life stages of insects feed on different plant parts and different plant stages. Usually, mortality rate of host plant increased because of attack on seeds. In some cases, insects can kill seedling (e.g., reproduction weevils) and mature trees (e.g., spruce budworms and bark beetles). Several groups of insects are present in the category of insect predators including defoliators, tip feeders, flower feeders, root feeders and stalk feeders (Peterson and Higley 2001).

3.2.2.2. Insects as Parasites

In this type of interaction, insects act as parasites on plants and the host is not killed by the parasites. Numerous insects fit into this category, for example; most sap sucking insects, some phloem-feeding insects, wood boring insects and gall forming insects (Peterson and Higley 2001).

3.2.2.3. Insects as mutualists

In this category, both partners are benefited without harming each other. e.g. pollination and predation. In insect pollination, plants obtain benefit through efficient transfer of pollen grains and the insect is benefited with its food (nectar). Predacious ants are attracted as results of secretion of extra floral nectararies of some plants that ultimately limit activity of other herbivores (Stephenson 1982). Production of honeydew because of feeding of aphids attract a wide variety of predacious Hymenoptera (Gilbert 1979).

3.3. Tritrophic relationship

Some insects are pests because they act as a disease vector and/or cause economic losses. These types of insect-plant interactions have occurred in nature for years ago with the presence of and coevolutionary arms race between these categories of real world. Entomologists are interested in insect-plant interactions with reference to sustainable production of agriculture crops. This approach involves the study of plant and herbivores communications in their related food chains. An important review is written by Price et al., (1980) which highlighted the significance of the third trophic level (natural enemies) along the first two trophic levels (plant and herbivore) in the studies of insect-plant interactions.

Price et al., (1980) highlighted the following elements:

1) Plants in the ecosystems are an important constituent of land communities which are collectively made of three interconnecting trophic levels (Begon et al. 1986)
2) Third trophic level is an important constituent of the theory of "Insect-Plant Interaction" and without considering it, no practical approach can be successful (Price et al. 1980)
3) Natural enemies as a third trophic level should be an ultimate part of natural plant defense complex (Poppy 1997)

3.3.1. Why study tritrophic systems

The ecosystem is a setup based on interaction of organisms belonging to the various trophic levels. These interactions control the physiological, ecological and behavioral features of collaborators. Due to these multiple responses between plants and herbivores, the behavioral and ecological scientists studied the multitrophic relationships between insect and plants. While multitrophic approach is currently dominated by tritrophic interactions. It is recognized that now-a-days, the fourth trophic level, enemies of natural enemies, is of great importance due to its influence on whole chain of tritrophic system.

3.3.2. Components of tritrophic interactions

Parasitoids and herbivore can affect each other through direct and indirect forces. For example; affecting host suitability are the indirect or negative effects; however, providing food and shelter and influence the source searching processes are direct or positive effects. The predatory effectiveness of any biocontrol agents can be influenced indirectly by plant mediated chemical and physical responses (Price 1981).

The major perspective of every constituent of trophic interaction is to maintain or increase its population and to find suitable host for its offspring can complete their dependent life span. The important factors in trophic interactions are host and its habitat, host acceptance by the next trophic levels, suitability of the selected host and its regulatory and nutritional requirements.

Usually, third trophic level particularly parasitoids use their visual and odour cues to search the proper habitats instead of the host habitat. The host/guest population dynamics is also influenced by the spatial distribution of host plant species in the habitat (Read et al. 1970).

Besides the host plants, other plants within the habitat may also offer food and shelter to the parasitoids; however, some parasitoids are only dependent on particularly plants for their food (Jervis and Kidd 1996) and try to depend on any plant as a host in certain locality (Powell 1986). The higher parasitoid population in an area may also be due to the availability of nectar and pollen. Parasitoid longevity, fecundity and mortality are increased by nectars and pollens produced by plants. For example; *Microplitis croceipes* C., a parasitoid prolonged its life span and parasitizing efficiency on larvae of *Helicoverpa zea* L. feeding on the nectaries of cotton plants compared to those larvae fed on nectarless cotton plant (Stapel et al. 1996). So, for the support of biological control, the habitat should be managed as an important tool (Powell 1986).

When parasitoids reached at their habitat, they still need to find their appropriate hosts just like herbivores (Sec. 3.2). They cannot find their proper host by random searching. Parasitoids use visual and particularly chemical cues to find their host location. These chemical cues are known as infochemicals, which regulate the message between the constituents of various trophic levels in certain environments. When parasitoids use these infochemicals to find their hosts, they face the "reliability-detectability problem" (Vet and Dicke 1992), however; these signals produced by the hosts are reliable but are not very easily detectable by the parasitoids (Turlings et al. 1993).

Vet and Dicke (1992) and Turlings et al. (1993) suggested three ways through which the problems of low detectibility of reliable cues can be diminished or overcome;

1) Chemical signals from various host stages should be practiced that are more discernible.

2) Go with easily detectable chemical cues among the signal complex.
3) Induced defense signals are more detectable over undamaged host plant cues.

Herbivore-induced plant volatiles (HIPV) are the substances released by the plants after the herbivore attack. They can easily be detected by noticing the wind direction. One of the examples of HIPVs is bean plants that induce response against aphid infestation (Du et al., 1996). Normally these induced volatiles are released from all leaves of the plant instead of only damaged leaves. Furthermore, the production of induced volatiles is dependent on amount of damage and aphid population, for example; in the case of bean plants, 40 aphids for 72 hours are required for a plant to induce parasitoid response (Guerrieri et al. 1996).

3.3.3. Chemical facilitated tritrophic interaction

In an ecosystem, all the living organisms are biochemically linked in a relationship which connects them in various food combinations. At least three trophic levels are present in a simplest connection of food chain. Each trophic level in this connectivity is evolved from the cost of higher energy level (Price et al. 1980). Furthermore, symbiotic relationship at each level of tritrophic interaction is present in every food chain. The biocontrol agents favor plants by reducing the herbivore populations and in return, plants favor them by making herbivores more vulnerable to them by altering the food chemistry of herbivores. Different factors are involved in such tritrophic interactions; the most important one is semiochemicals. These semiochemicals bring behavioral and physiological changes in the receiver (herbivores) and as a result the interaction are developed (Nordlund 1981). Moreover, these changes cause attraction, repulsion, arrest and detraction types of responses in herbivores (Ruther et al. 2002).

3.3.4. Types of semiochemicals

Semiochemicals are mainly divided into two classes, pheromones and allelochemicals. Pheromones are categorized as intraspecific semiochemicals, which mediate interactions between the organisms of same species, such as interaction between insects or between plants. These are further classified into different types based on their performance, for example; sex pheromones, alarm pheromones, aggregating pheromones etc. (Nordlund 1981). However, allelochemicals are interspecific semiochemicals, having great importance for communicating the organisms of different species and play a significant role in tritrophic interactions. These are further classified into allomones, kairomones and synomones. According to Ruther et al. (2002), allomones are the chemicals which are released and performed in favor of emitter, however; the chemicals that are favorable for both, the donor and the recipient are known as Synomones, whereas the chemicals released in favor of receiver only are known as kairomones.

According to Nordlund (1981), these categories of allelochemicals can be used interchangeably depending upon the receivers and emitters, including plants, herbivores and natural enemies. The terpenoids released by pine trees act as allomones for plant itself (Smith 1963) whereas same chemical cues are used by bark beetle for finding its food, hence may be considered kairomones for beetles and synomones for the predators of bark beetle which are being attracted using the same chemicals (Wood 1982). Furthermore, these semiochemicals can be categorized into plant produced and insect produced based on their sources.

3.3.4.1. Plant-based volatiles

Semiochemicals which are produced by plants act as intrinsic defense against herbivores. Although, third trophic level may also be affected by these chemicals which result in tritrophic interaction (Ahmad et al. 2004). The plant volatiles, food and floral scent are used as synomones by beneficial insects especially pollinators (Leius 1967; Pellmyr and Thien 1986). The predators locate their potential host, a herbivore, which is also feeding on the same plant with the help of these cues. Nectar is one of the major reasons to attract some parasites and predatory ants (Bentely 1977; Smiley 1978). Plant odors are also a significant feature in tritrophic relationships (Read et al. 1970; Vinson 1984). The coccinellid predator of pine aphid, *Anatis ocellata* L., used the odor of infected pine needles to locate its prey (Kesten 1969).

Mostly natural enemies are omnivores throughout their lives feed on herbivores during their immature stages and use plant nectars as food during adult stages (Hagen 1986). This feeding division of natural enemies is advantageous for plants as well as for themselves (Hespenheide 1985). However, the efficiency of natural enemies to find their hosts at any life stage depends upon the quality of food and cues offered by host plants and preys (Sundby, 1967; Foster and Ruesink 1984). The Mustard aphid, *Brevicoryne brassicae* L. and its parasitoid *Diaeretiella rapae* M. is a known example of tritrophic interaction mediated by compound, sinigrin released by mustard plant (Read et al. 1970).

Therefore, quality of the interaction is affected by the physical factor of the emitter, such as size, vigor, growth and survival rate of the hosts (Ahmad et al. 2004). In case of plants, secondary metabolites are responsible for deterrent effects on insect pests and in result increase the efficacy of natural enemies of that particular herbivore. *Aphytis melinus* D., a predator of Californian red scales, *Aonidiella aurantii* M., can utilize host of about 0.39 mm^2 and larger, while *Aphytis linginanenis* D. can feed the prey size of 0.55 mm^2 and larger (Luck and Podoler 1985).

3.3.4.2. Herbivore-based volatiles

Herbivores are the main component of tritrophic interaction that links the upper and lower level in a chain. Hence, in case of tri/multitrphic interaction, herbivores face the intrinsic and extrinsic defenses by plants and their natural enemies at the same time. Therefore, plants release the secondary chemicals that are not only used in plant defense against herbivore but also enable predators and parasitoids to search their prey. The chemicals produced by Lycaenid butterfly larvae and aphids that intimate an association between herbivore and predator also act as synomones for predatory ants to protect the herbivores from natural enemies, so a mutualistic interaction is developed between ants and the aphids (Way 1963; Atsatt 1981; Pierce and Mead 1981).

Volatiles (kairomones) are produced by plant feeders and are perceived by natural enemies. These cues may be in form of body smell or order to become a source of attraction for the biocontrol agents particularly parasitoids (Loke and Ashley 1984; Noldus and van Lentern 1985). These kairomones may also be released in form of sex pheromones (Sternlicht 1973; Kennedy 1984), aggregation pheromones (Wood 1982), excretory products (Lewis and Jons 1971; Nordlund and Lewis 1985), body scales (Loke and Ashley 1984) and eggs (Jones et al. 1973). One of the significant examples of body odour detection is found in bee wolf, *Philanthus triangulum* F., a predatory wasp that detect the bees through their body smell and is an example of foraging pheromones (Longhurst and Howse 1978; Howse 1984; Ruther et al. 2002).

Furthermore, allomones an important constituent of tritrophic interaction work against either plants or natural enemies and in favor of insect herbivores. Several compounds can be derived from herbivores that to utilize as allomones.

3.3.4.3. Predator-based volatiles

Chemical compounds released by natural enemies cannot be ignored in these interactions of plant and insects as these volatiles play a vital role in altering the plant physiology according to the requirement. For example, *Piper cenocladum* (family: Piperaceae) responds to synomones released by third trophic level (predators) and perceives the presence of obligatory ants, *Pheidole bicorins* F. then produces food bodies (Risch and Rickson 1981).

Natural enemies also produce some kairomones and allomones (Ruther 2002). When these kairomones are detected by herbivores, they run away from the source to avoid their enemies (Dicke and Grostal, 2001). Large number of predatory hymenopterans like ants, wasps and bees respond to kairomone, formicid, to avoid predatory ants in dry-land ecosystem (Chadab 1979). In the same way, some chemicals perform the function of allomones and are used by the predators to mimic the body of their preys (Vander Meer and Wojcik 1982).

3.3.5. Phenomena of plant-mediated interactions between insect herbivores

3.3.5.1. Induced resistance

Herbivores feed on host plants and thus plants produce allelochemicals to resist their feeding (Karban and Baldwin 1997; Constabel 1999). These allelochemicals are defensive in function and include phenolics, terpenoids, alkaloids and glucosinolates (Karban and Baldwin, 1997; Constabel, 1999).

Moreover, herbivores colonization at early stages of plants can induce changes in plant morphology such as leaf structure, trichomes, bud formation and branching structure (Karban and Baldwin 1997). These herbivores induced structural changes in host plant after insect feeding may have positive or negative effects on the subsequent feeders. For example, trichomes in leaf (Agrawal 1998, 1999; Traw and Dawson 2002) and variation in floral patterns and size (Strauss 1997) produce adverse effects on subsequent feeding insects. So, these morphological alterations in plant structure can be further utilized for discouraging the herbivore feeding on the specific host plants.

The herbivore feeding on plants also mediate the nutritional imbalance in the food source for plants and cause the malnutritioning for herbivores. In return, herbivores stop feeding on these plants. Moreover, their initial feeding on host plant stimulates plant defensive system that ultimately attracts the natural enemies at the specific site and location (Vinson 1998; Pare et al. 1999).

3.3.5.2. Induced susceptibility

In this phenomenon, host plant chemicals repel one type of herbivore, while attract other. For example, *Pieris rapae* L. larvae induce glucosinolates and some other volatiles while feeding on wild reddish that are used by the monophagous flea beetle, *Phyllotreta* sp. to locate its host (Agrawal and Sherriffs 2001). In the same way, changing plant structure after herbivore feeding can also help to attract the other herbivores for food and shelter (Ohgushi 2005).

Therefore, induced changes after herbivore feeding can be utilized to repel the one kind of herbivores and attract the any other specialist herbivore on the same host plants.

3.4. Host-plant resistance

3.4.1. Resistance mechanism to insects

The resistance is either a constitutive or an induced mechanism (Painter 1951; Karban et al. 1997; Karban and Agrawal 2002; Traw and Dawson 2002). Generally, based on physiological function, the resistance in insects can be classified into three major categories that are antixenosis (nonpreference), antibiosis and tolerance (Painter 1951).

3.4.1.1. Antixenosis

Antixenotic mechanism of resistance is employed by the host plants that deter the insects from oviposition (Painter 1951; Valencia 1984; Karban et al. 1997; Afzal et al. 2009), feeding, seeking shelter (Dabrowski and Kidiavai 1983; Woodhead and Taneja 1987; Sharma and Nwanze 1997) and establishment (Dhaliwal and Arora 2003). This mechanism makes the plants undesirable or likely not to be the hosts for insect invasions (Bazzaz et al. 1987; Dhaliwal and Arora 2003). Antixenotic characteristics develop in a plant due to certain morphological characters, allelochemicals (Kogan 1982; Rhoades 1983; Edelstein 1986; Edelstein and Rausher 1989; Adler and Karban 1994; Morris and Dwyer 1997; Thaler 1999; Afzal et al. 2009) or interactions between these factors (Panda and Khush 1995). These features result in one or more breaks in the continuous responses of insect oviposition and feeding (Panda and Khush 1995; Dhaliwal and Arora 2003). Following are types of no preference found in litreature:

Allelochemical nonpreference

This is a much-known phenomenon among plants and sometimes makes them non-preferred by herbivores. Some examples include spotted cucumber beetle, *Diabrotica undecimpunctata howardi* M., and other *Disbrotica* species found on cucurbits show allelochemic nonpreference. In this type of insect plant relationship, cucurbits release a chemical, cucurbitacins which acts as attractant and feeding initiating for few coleopterans. In this way, only few beetles are attracted and plants receive low level of damage compared to the plants with more feeding by beetles on them which lack or less levels of specific cucurbitacins (Pedigo and Rice 2009).

Morphological nonpreference

The morphological nonpreference occurs because of plant features and structures that cause disturbance and interruption in the normal behavior of insect feeders. For example; *Helicoverpa zea* L. (corn earworm), prefers pubescent surfaces for oviposition. Furthermore, litreature shows that cotton varieties with no hairs are suffering less damage by many insect species because of lower rates of oviposition compared to those varieties having hairs on the leaves and other plant parts (Pedigo and Rice 2009).

Some other examples of morphological nonpreference are; husk tightness in corn, stem density and node tissues in wheat and woody stem in cucurbits that help to reduce injury by corn ear worms in maize, by wheat stem sawfly (*Cephus cinctus* N.) in wheat and by squash vine borer, *Melittia cucurbitae* H. in cucurbits respectively (Pedigo and Rice 2009).

3.4.1.2. Antibiosis

Antibiosis occurs when the physiochemical qualities of the plants cause decrease in life history such as survival, egg laying capacity reproduction and developmental rates of the arthropods. Heavy pubescence, increased cuticle thickness and sticky masses on various plant structures that slow down the feeding and continuous growth of the arthropod are some of the physical reasons of antibiosis. Presence of secondary compounds such as allelochemicals or lack of nutrients needed by the arthropod, such as essential amino acids etc. is some physiological antibiotic reasons in plants (Painter 1951).

Normally, allelochemicals and antibiosis are interconnected. The cyclic hydroxamic acids in corn (DIMBOA, 2, 4-dihydroxy-7-methoxy-1, 3-benzoxazin-3-one), gossypol compounds in cotton, steroidal glycosides in potato, and saponins in alfalfa are few important examples of antibiotic compounds examples in various plant species (Pedigo and Rice 2009).

Primary metabolites, their quality and quantity play very important and significant role in determining the antibiosis in any plants. Most importantly, sugar and amino acids imbalance cause malnutrition in insects feeding on that particular plant. For example, resistance is observed in pea cultivars due to low amino acid levels and higher sugar contents against the pea aphid, *Acyrthosiphon pisum* H. Reduced reproductive and egg laying capacities is observed in the brown planthopper, *Nilaparvata lugens* against the rice cultivars with low asparagines (an amino acid) (Pedigo and Rice 2009).

3.4.1.3. Tolerance

Tolerance is defined in numerous ways and researchers have argued whether it is truly a part of host plant resistance, because no deleterious effects have been produced in the insects. Painter (1951) categorized the resistance mechanisms as tolerance, antibiosis and nonpreference (now antixenosis) for the first time (Kogan and Ortman 1978). He defined tolerance as "a basis of resistance in which the plant shows an ability to grow and reproduce itself or repair injury to a marked degree despite supporting a population approximately equal to that damaging a susceptible host" (Painter 1951).

In case of tolerance, the level of feeding or damage by sucking and chewing insects, do not cause any expression but it is a response of plant to a given level of damage. Rapid foliage growth in Lucerne (*Medicago sativa*) after the attack of alfalfa weevil (Dogoer and Hansonc 1963) and speedy tiller production in sorghum followed by the attack of sorghum shoot fly (Doggett et al. 1970) are the examples of tolerance, like the development of secondary and thick roots in maize (*Zea mais*) followed by the damage of corn root worm (Owens et al. 1974).

Tolerance is basically the effect of insect on plant (the less damage means the higher level of tolerance). As the recovery after insect injury is also a *plant* response, that is why it is a part of tolerance. However, recovery from injury has been investigated very little. A rare exception is the work of Morgan et al. (1980). Tolerance should be more useful in a pest management program than antibiosis or antixenosis because of compatibility with other control strategies and biotype considerations.

3.4.2. Genetic basis of resistance

3.4.2.1. Epidemiological types of resistance

A lot of work of plant pathologists on this classification of resistant types has been done to express its the effectiveness and stability against a pest population. Plants genes are used to determine the effectiveness and stability of different resistant varieties. Resistance and the insect genes which allow the resistance to be overcome are conferring by these plant genes (Pedigo and Rice 2009).

The gene-for-gene relationship

Several pest populations include those individuals which have virulent genes that allow a pest species to overcome resistance and further attack a plant. Effect of one or more plant genes responsible for resistance overcome with the order of an individual that has one or more virulent genes. This principle has been called the gene-for-gene relationship (Pedigo and Rice 2009).

In this type of relationship, plant cultivars are resistant because resistant alleles are present at gene locus responsible for avirulence (susceptible) at a specific locus in the insects. Even the resistant cultivar is effective against several insects present in the population. Pedigo and Rice (2009) explained that avirulent allele is absent in an insect, it has only virulent allele. For example; host plants having resistant genes may code for a protein toxic to the insect, and insect having a respective virulent gene may code for an enzyme which are used to detoxifies that specific toxin present in the plant. By this situation, virulent individuals attack the other resistant plant and avirulent genotype can be replaced by virulent genotype for a long-time period. The effectiveness of the resistant cultivar ultimately would minimize (Pedigo and Rice 2009).

Different populations of an insect species which differ in their virulence to the cultivar are known as Biotype. The Hessian fly, *Mayetiola destructor* S. has several biotypes. The term biotype is often used for certain insect populations that overcome plant resistance (Pedigo and Rice 2009).

To date, most insect biotypes have developed in aphid. Spotted alfalfa aphid, *Therioaphis maculate* B. on alfalfa; corn leaf aphid, *Rhopalosiphum maidis* F. on sorghum and corn; greenbug, *Schizaphis graminum* R. on wheat and sorghum and pea aphid, *Acyrthosiphon pisum* H. on peas and alfalfa are the well-known examples (Pedigo and Rice 2009).

3.4.2.2. Vertical and horizontal resistance

Van der Plank (1963) recognized two types of resistance based on effectiveness of a resistance i.e. vertical and horizontal resistance. Vertical resistance refers to the cultivars having resistance limited to one or a few pest genotypes. Horizontal resistance refers to those cultivars that express resistance against a wild range of genotypes.

Some authorities have debated against vertical resistance in breeding programs because of the potential development of biotypes. But in case of Hessian fly on wheat, this type of resistance is successful and is simplest to incorporate into new varieties compared to horizontal resistance. It has been suggested in case of managing insects by using vertical resistance, identification of resistant genes in plants is necessary and may be incorporated into varieties and then released when biotypes appear (Pedigo and Rice 2009).

Horizontal resistance has low heritability and has many difficulties in incorporation for plant breeders. However, some success stories of horizontal resistance are observed such as cultivars of corn with high resistance to both generations of the European corn borer, *Ostrinia nubilalis* H. Moreover, due to stability of horizontal resistance, it is the most desirable type of resistance which is used in management of pests (Pedigo and Rice 2009).

3.4.3. Resistance classes on inheritance

Plant resistance can also be distinguished based on mode by which it is inherited. Three major categories of resistance are recognized by Day (1972) which are; oligogenic resistance, polygenic resistance and cytoplasmic resistance.

3.4.3.1. Oligogenic resistance

This type of resistance is also known as "major-gene resistance" and carried by one or more genes. Vertical resistance is produced by this type against insects and may be inherited through dominant or recessive genes. Single-gene dominant resistance has been incorporated into varieties of different crops such as cotton, apple, rye, raspberry, sweet clover and rice. Single-gene recessive resistance can be found in corn lines which are resistant to the Western corn rootworm and wheat resistant to the greenbug. Another example of oligogenic resistance is wheat resistantance to the Hessian fly, nevertheless, resistance is conferred by a series of dominant or partially dominant genes, as well as by numerous recessive genes. Resistance is often considered oligogenic in this example because a well-understood gene-for-gene relationship exists between resistance genes in wheat and the corresponding virulence genes in the Hessian fly (Pedigo and Rice 2009).

3.4.3.2. Polygenic resistance

This type of resistance conferred by many genes and each have the resistance effect. For this reason, this is also known as "minor-gene resistance". Resistance inherited through the polygenic mode is usually very complex and may be associated with such quantitative traits as plant vigor and yield. Horizontal resistance is usually polygenic. An example of polygenic resistance, as already mentioned, occurs in corn varieties resistant to the European corn borer (Pedigo and Ricw 2009).

3.4.3.3. Cytoplasmic resistance

This type of resistance is conferred by mutable substance (capable or liable to mutation) substances in cell cytoplasm. Cytoplasmic inheritance is maternal because most cytoplasm of the zygote comes from the ovum. Although cytoplasmic inheritance is very important in resistance to pathogenic microorganisms, it has not been a factor in resistance to insects (Pedigo and Rice 2009).

3.5. Case study

In studying plant-insect-interaction, the Hessian fly, *Mayetiola destructor* S. offers the best example of several aspects of insects and plants and co-evolution. This insect illustrates the classical example of genetic variation both in the insect and the plant. For example, wheat is known for having resistant genes against this insect. However, it was not until the genetic components of resistance in the plant and virulence genes in the insect were identified that the first clear evidence for the gene-for gene relationship was described. Gallun (1977) was the first to show that the relationship that Flor (1942) identified for a pathogen in flax was true for an insect in wheat. Most genes for resistance to the Hessian fly are major genes, also referenced as antibiosis genes also known as vertical genes. These resistance genes provide the basis for strong selection advantage for those insects with low frequency of virulence genes. After several generations, there is a shift in local populations to point that insects with the virulence genes are predominant. In lay terms, the insect population has now overcome the resistance genes in the wheat plant. Hence, the value of the resistance in the plant is minimized and the breeders must release new resistance genes in the plant that can withstand the local populations of the insect in "niches" or fields. Resistance in the plant is controlled by a dominant gene; however, avirulence in the insect is controlled by a recessive allele in the fly, hence virulence in the insect confers susceptibility in the plant. This is the classical gene-for-gene relationship in plant insect interaction.

The expression of resistance in host plants has been affected by both biotic and abiotic factors. In soybeans, plant resistance has been shown to be both constitutive and inducible. For example, insect abrasion or injury by any mechanical means may induce resistance in many crop plants (Smith 1989). Such as, induced resistance in soybeans, *Glycine max* has been documented (Kogan and Fisher 1991). Mechanical damage to soybean foliage also causes to induce the resistance against the soybean looper. Wound induced resistance in soybean has been shown to retard the development and growth of both the Mexican bean beetle and soybean looper as well. The induced resistance has been shown to be correlated with raised levels of several plant natural products.

3.6. Conclusion

The complexity of Plant-Insect-Interaction makes it difficult to concise a single chapter. The main relationships between insects and plants from Paleozoic to present times are discussed. Arthropods, more specifically insects make up the major portion of plant feeders. The concept of coevolution was first raised by Ehrlich and Raven (1964). Some authors express that this may be a pre-adaptation by plants.

Plants, mostly green plants, are the major source of energy for most food chains. In phytophagous species, it is difficult to find most advantageous form, monophagy or polyphagy. It is true that polyphagous species have a much greater choice of host plants. True phytophagous insects account for about 50% of the living insects. Toxic plants transmit their toxicity to insects and protect them indirectly. However, that toxicity of plants is not always responsible for toxicity of insects to their predators. Host plant selection in insects is dependent on many factors like visual, olffactive, gustative and chemical reasons. Additionally, the quality of the plant, life stage and rapidity of the development and vigor of the insect also effect the host plant selection.

Clearly, food selection has a strong influence on a species. Selection is often the function of existing pre-adaptation to a given diet (host). Regarding choices, polyphagous species have more chances to evolve quickly than monophagous species. However, this is not a hard-fast rule as illustrated by biotypes of insects on resistant crops cultivars where coevolution has been amply demonstrated numerous times and where we frequently have referred to the gene-for-gene in the insect and the plant. This concept has gone under some strong critiques and now the prevalent thinking is that this co-evolution is more complex than was earlier thought. During the evolution of a crop plant and the host insects, equilibrium exist at some time between the plant and insect, if both were to survive. This co-evolution must have occurred between the plant and the insect as the host plants accumulated genes for resistance and the insects accumulated genes for virulence.

The chemical cues produced by the plants and intercepted by the insects can be utilized in generating the phenomenon of pest management in a specific site. The artificial synthesis of these compounds or manipulation of naturally produced chemicals can play a dynamic role in this field of sustainability of pest management. Keeping in view the interactions among the trophic levels discussed in various sections of the chapter, the proper utilization of these interactions and associations in this domain can be whole success with reduced use of risk carrying chemical control methods.

Table 1 Categories of Insect-Plant Interactions

Insects	Plants
Predators, parasitoids	Prey
Parasites	Host
Pollinators, seed dispersal agents	Provide a reward
Allelopathic agents, antiherbivore defense force	Provide a reward and a certificate of residence
Nutrient gatherers	Certificate of residence
Host	Parasites
Prey	Predators

Source: Gilbert (1979)

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Chapter 4

Insect Pests of Important Field Crops

Khuram Zia, Ahmad Nawaz and Muhammad Sajid†

Abstract

Current article is intended for the integrated pest management of major and minor insect pests of important crops (cotton, wheat, rice, corn and sugarcane) of Pakistan. The insect pests cause qualitative as well as quantitative crop losses. In addition, they transmit plant pathogens which increase damage percentage. Precision and sustainable agriculture success is based on integrated pest management practices like cultural, mechanical, physical, biological, legislative and chemical control. These practices are collectively helpful to manage major and minor insect pests. The pest status (major or minor) of insects has been fluctuating with changing environment. Cultural, mechanical and physical control methods take more time and are less efficient than other control methods. Biological control is somewhat complex as it is based on the use of various predators, parasitoids and entomopathogens whose lifecycle must synchronize with that of their host. Introduction, augmentation, rearing and release of natural enemies are important. It leads biological control to a complex control practice which is somewhat difficult to achieve. The last control option in the integrated pest management is the chemical control that is quick and broad spectrum in nature but has mammalian toxicity. Therefore, the integration of chemical control with other control measures is necessary to minimize the use of toxic chemicals in the environment for crop production.

Keywords: Insect Pests, Agronomic crops, Biological control, Management, Rice, Maize

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4.1. Importance of crops

Agriculture sectors contribute near about 20.9% share in Gross Domestic Products (GDP) of Pakistan. It is a source of livelihood of more than 43.5% population of Pakistan's rural areas. Precision and sustainable agriculture is needed to reduce the poverty and food insecurity in Pakistan. Current issues in agriculture sector are low returns to farmers due to high input and low outputs due to different factors including insect pests. There are two cropping seasons (Kharif and Rabi) in Pakistan. Kharif season is from July to October while Rabi season is from October to April. The crops grown between March and June are known as summer crops. The important crops of both season like cotton, rice, maize, sugarcane and wheat added value up to 25.6% in overall agriculture sector and 5.3% in GDP.

In cotton (*Gossypium hirsutum*) production, Pakistan stands 4th in the world. It is an important fibre crop and vastly grown in the Sindh and Punjab provinces of Pakistan and contains 80% oil content (Agha 1994). It is major source of foreign exchange and contributed 1.5% and 1.7% in GDP and agriculture value addition respectively. The area under cotton cultivation is around 3 million ha. Cotton is major source of raw material for the industries including ginning, oil and textile (Ghani 1998). Both sucking and chewing type of insect pests attack on cotton. The American cotton (germ plasm from USA) is more susceptible to insect pests than Desi (native to Pakistan) cotton of Pakistan (Saeed et al. 2007). In response to changing environment, the status of various pests has been shifted from secondary to primary insect pest (Dhaliwal et al. 2010).

Wheat (*Triticum aestivum* L.) is an important source of carbohydrates and leading source of vegetal protein in food. It has protein content of about 13%. Wheat is the staple food of Pakistan and cultivated on around 9.18 million hectares during 2014-15. Wheat share in GDP during 2014-15 was 2.1% and 10% in agricultural value addition. Several insect pests attacked wheat and utilise the plant for food reducing quality and causing economic damage.

Rice (*Oryza sativa* L.) is the second largest staple food of Pakistan. Area under rice cultivation is around 2.89 million hectares in Pakistan. Rice contribution in GDP and agricultural value addition was 0.7% and 3.2% respectively. It is the first perennial, terrestrial specie which adapted aquatic ecosystem. Rice attacked by more than 70 insect species in Pakistan, which cause 25-30% yield losses (Hashmi 1994).

Sugarcane (*Saccharum officinarum* L.) is another important cash crop in Pakistan and cultivated for sugar and sugar related products. It serves as raw material for paper and board industries. Its contribution in GDP and agriculture value addition is 0.6% and 3.1% respectively. The area under sugarcane cultivation in Pakistan is 1.14 million ha and Pakistan earned around US$171.78 million from sugarcane export. Among 105 sugarcane growing countries, Pakistan occupied 4th and 60th position for cultivated area and per hectare production respectively (Azam and Khan 2010). The yield of sugarcane is affected by many factors such as soil fertility, climate, variety, cultural practices, disease and insect pests (David and Nandagopal 1986). More than 1500 insect species have been recorded on sugarcane. Both chewing and sucking insect pests take part in quantitative and qualitative losses of sugarcane (Zia et al.

2007) causing around 20% yield loss of sugarcane and 15% decrease in sugar recovery (Avasthy 1977).

Maize (*Zea mays* L.) known as “King of Grain Crops” is the third most important cereal crop in Pakistan. Up to 8-10% of the maize crop is used for human consumption. It is big source of food, feed and fodder. It also provides starch, glucose and corn oil as by-products (Chaudhary 1983). Maize starch is rich source of bio-fuel across the world and provides ethanol after its fermentation (Ahmad et al. 2007). In addition, it is used as energy source at home and in industry as feed for chicken (Kellems and Church 2010). In Pakistan, maize contribution is 0.4% in GDP and is sown in 1.1 million hectares. Major maize production is contributed by K.P.K. and Punjab. Average maize production of country is very low in comparison with other countries of the world (Ahmed et al. 2003). Insect pests decreased the yield more than 15% of the total annual crop production (Boulter et al. 1989; Kumar et al. 1992).

Around ten thousand species of insects affect the food plants worldwide, out of them 10% are considered as major pests (Dhaliwal et al. 2010). Various control measures are being adopted to control insect pests (Dhaliwal and Koul 2010). The insect pests of major field crops are discussed below.

4.2. Cotton

4.2.1. Dusky cotton bug

Technical Name: *Oxycarenus laetus* Kirby

Family: Lygaeidae

Order: Hemiptera

Identification

Fresh eggs are oval and cigar shaped. Female laid eggs are transparent and light yellowish in colour. The colour of the eggs changed to light pinkish before hatching. Nymphs have round abdominal end. They are initially pale greenish to parrot green in colour somewhat resembling aphid (*Aphis gossypii* Glov.). Adults are 4 to 5 mm with reddish brown to dark brown in colour having distinction of well-developed glassy transparent wings which are absent in nymphs (Fig. 4.1) (Panwar 1979).

Biology

Eggs are normally placed in the lint of partially opened bolls between the slaps in isolated or group fashion of 3 to 18 eggs per cluster. Eggs hatched after 5 to 10 days. Nymphal period lasts for 31 to 40 days. Nymphs pass 7 stages to become adult. Wide numbers of generations (3-4) are completed in one year and each generation may range of about 20 days.

Fig.4.1 Dusky cotton bug, *Oxycarenus laetus* K. (Photo credit: S. Zahid, UAF)

Damage

Nymphs and adults of DCB de-sap the seeds inside the developing bolls. Seeds do not develop properly and remained weak. They are also known as cotton strainers extensively present on lint and finally get crushed in ginning vicinities. Thus, it colours the lint with bad patterns. Such kind of lint does not get desirable market value (Panwar 1979).

Management

Cultural control

All infested plants should be removed from the fields along with host weeds. Alternate hosts like cotton and okra should not be sown in the same or nearby fields (Panwar 1979).

Biological control

An anthocorid bug *Oriustantilus* has affinity of prey for nymph of dusky cotton bug (Panwar 1979).

Chemical control

The important pesticides for effective management of DCB are Thiamethoxam (Actara ST 70 WS) 3 g kg^{-1} seed for seed treatment, Profenofos (Curacron 500 EC) 2000 ml ha^{-1}, Lambda-Cyhalothrin (Karate 2.5 EC) 800 ml ha^{-1} Diafenthuron (Polo 500 SC) 500 ml ha^{-1} and Profenofos + Cypermethrin (Polytrin C 440 EC) 1500 ml ha^{-1} (Panwar 1979).

4.2.2. Cotton Jassid

Technical Name: *Amrasca biguttula biguttula* Ishida (Distant)

Family: Cicadellidae

Order: Homoptera

Identification

Eggs are pale to yellowish in colour. Both immature and adults are very active and can move sideways as well as forward. Nymphs are yellowish green to parrot colour (Panwar 1979). In winter season, adults (Fig. 4.2) seemed to have reddish brown sensation with dark purple eyes (Pimentel 1991). Nymphs are like the adults but are smaller in size with no wing possessions (Panwar 1979).

Biology

Eggs are laid on the lower surface of the leaves. They can be fixed in the veins or veinlet of leaves and are about 15 in numbers (Panwar 1979) leading to maximum of 29. Eggs may also be placed inside the leaf tissues which can be seen by cutting the leaves under high magnification microscope (Pimentel 1991). Nymphs are brought forth from these eggs in about 4 to 11 days. Nymphs pass 6 instars in 7 to 21 days to become adult. Cotton jassid can complete 7-11 generations in a year during favourable conditions (Panwar 1979; Vennial et al. 2007)

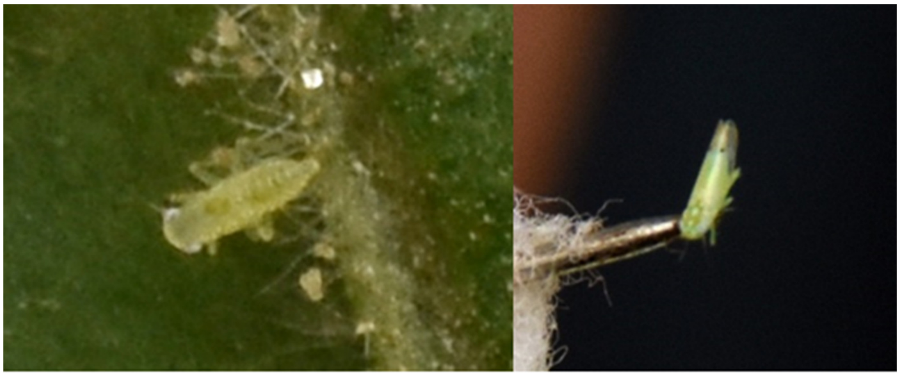

Fig.4.2 Cotton jassid, *Amrasca biguttula biguttula* D. (Photo credit: S. Zahid, UAF)

Damage

Nymphs as well as adults suck the plant juice from the lower surface to the plant leaf (Panwar 1979). Effective management of cotton jassid can increase 22 to 53% crop yield (Sidhu and Dhawan 1978). During sap sucking, cotton jassid also inject toxic chemical into the plant leading to typical leaf curling, yellowing, brick red appearance and eventually falling of leaves after drying. Fatal infestations may lead to the decrease in yield of about 35% (Panwar 1979). Fruiting ability of the plant is also impaired with more injurious attack of jassid (Vennila et al. 2007).

Management

Cultural control

Cultivation of resistant varieties and treating the seeds with neonicotinoide insecticides (for hindrance of pest incidence for 45 to 50 days) are also good control measures (Vennila et al. 2007). All stray plants should be removed from the fields along with host weeds. Jassid population has the negative relations for leaf numbers and inter nodal distance whereas an increasing relation is seen to enhanced plant height (Mansah 2014). Therefore, selection of variety can be very important for the management of cotton jassid.

Biological control

Chrysopa cymbele and spider (*Distina albida*) have the strong voracity against this insect pest (Panwar 1979).

Chemical control

The ETL of jassid is 1 nymph or adult per leaf. There are different pesticides available for the management of cotton jassid. For example, Malathion 50 EC (800 ml ha^{-1}), Dimethoate 30 EC (1500 ml ha^{-1}) or Acephate 75 SP (500 ml ha^{-1}) are possessed to shown good results (Panwar 1979). Immidacloprid 200 SL (125 ml ha^{-1}) and Thiamethoxam 25 WG (250 g ha^{-1}) can be applied when the jassid injury reached at threshold level (Vennila et al. 2007). In addition, Diafenthuron 500 SC (500 ml ha^{-1}), Profenofos + Cypermethrin 440 EC (1500 ml ha^{-1}), Deltamethrin + Triazophos 360 EC (1200 ml ha^{-1}), Cyfluthrin + Methamidophos 525 EC (1200 ml ha^{-1}) are also effective for jassid control.

4.2.3. Whitefly

Technical Name: *Bemisia tabaci* Genn.

Family: Aleyrodidae

Order: Homoptera

Fig.4.3 Whitefly, *Bemisia tabaci* G. (Photo credit: S. Zahid, UAF)

Identification

Whitefly (*B. tabaci*) is a group with great genetic diversity of 17 prominent populations and 24 biotypes (Perring 2001). Eggs are semi white, stalked changing to brown in colour when near to hatch. Nymphs are yellow to bright yellow in colour and the body is impregnated with whitish waxy powdery material. Wings are pure white (Fig. 4.3) (Panwar 1979).

Biology

Stalked eggs are laid by the female on the lower side of the leaves in a separated fashion with an average number of 115 eggs. They hatch in 3 to 33 days in summer to winter seasons. Whole life cycle is completed in 14 to 120 days with 10-11 generations existing in a year time (Panwar 1979).

Damage

Whitefly causes both direct (sap sucking) and indirect (disease transmissions) damage to cotton crop (Byrne et al. 2000). After hatching, nymphs crawl for sometimes and then insert their mouth stylet to suitable place for feeding. Its lethal symptoms and damages can either be direct (lowering the plant vigour by inserting toxins from saliva) or indirect (producing sooty mould due to honey dew excretions and viral disease vector transfer) (Panwar 1979). Collective losses due to whitefly are assessed to millions of US dollars per year in a versatile agro ecosystem (Menn 1996). Host range of whitefly is recorded to be above 700 plant species occurring in 86 plant families (Greathead 1986). About 111 plant viruses owe due to its action and transmission (Horowitz et al. 2003; Mugiira et al. 2008).

Management

Cultural control

Cultivation of cotton varieties with glabrous leaf (i.e., smooth leaf surface) has least population of whitefly (Niles 1980)

Biological control

Both predators (green lace wing; *Chrysoperla* spp. and Brumus sp.) and parasitoids (*Eretmocerus massi*) can be effectively used for the biological control of whitefly (Panwar 1979).

Chemical control

Whitefly has developed resistance to about 40 insecticides used worldwide (Roditakis et al. 2005). The ETL of whitefly is 5 adults or nymphs or both per leaf. Use of Thiamethoxam 70 WS (3 g/kg seed) for seed treatment, Profenofos 500 EC (2000 ml ha^{-1}), Lambda-Cyhalothrin 2.5 EC (800 ml ha^{-1}) Diafenthuron 500 SC (500 ml ha^{-1}) and Profenofos + Cypermethrin 440 EC (1500 ml ha^{-1}) give effective results as spray. Chemical control with the old-fashioned insecticides and non-judicious use of new chemistry insecticides has lead it to difficult to manage insect context.

4.2.4. Red cotton bug

Technical Name: *Dysdercus koenigii* Fabricius

Family: Pyrrhocoridae

Order: Hemiptera

Fig. 4.4 Red cotton bug, *Dysdercus koeningii* F. (Photo credit: A. Nawaz, UAF)

Identification

Eggs are shining yellow in colour arranged in turbulent aggregations of 75 to 80 eggs. Nymphs have fluffy abdomen and bright red colour. Later on, black colouration appears on the body in different marks. Adults are slender and long with brick red colour (but variation exists for bright red in spring to early winter and light brown to pinkish brown adults in winter) with prominent strips across the abdominal body (Fig. 4.4). Soft part of their wings and scutellum are black while abdomen is reddish black in colour (Panwar 1979).

Biology

Eggs are laid in earthen cracks or humid soil on an average of 100 to 130 eggs. Young ones procreated from the egg in 7 to 8 days. There are 5 nymphal stages are present comprising of 49 to 89 days (Panwar 1979).

Damage

Adult and nymph suck cell sap from the soft plant parts reducing plant vitality. They also produce signs of bad boll opening. The sap sucking from the seeds decrease the seed vigour and hence making them least desirable for next sowing due to low germination capability. These insects also stained the cotton lint with their body crushing, waste products and secretions. Spoilage of lint may also be due to bacteria (*Nematospora gossypii*) taking entry during the feeding of red cotton bug into seeds inside lint cover (Saleem and Shah 2010).

Management

Biological control

Predatory bugs such as Pyrrhocorid bug *Antilochus cocqueberti* and Reduviid bug *Harpactor costalis* are good feeders of both immature and mature stages of red cotton bug (Panwar 1979).

Chemical control

The chemical insecticides such as Thiamethoxam 70 WS (3g/kg seed) for sead treatment while Profenofos 500 EC (2000 ml ha^{-1}), Lambda-Cyhalothrin 2.5 EC (800 ml ha^{-1}), Diafenthuron 500 SC (500 ml ha^{-1}), Profenofos + Cypermethrin 440 EC (1500 ml ha^{-1}) give reliable results (Panwar 1979).

4.2.5. Cotton Thrips

Technical Name:	*Thrips tabaci* Lindermann
Family:	Thripidae
Order:	Thysanoptera

Fig. 4.5 Cotton thrips, *Thrips tabaci* (Reproduced with permission by: http:///www.invasive .org)

Identification

These are very minute insects with slander shape bodies. Adults have clear wings with slight hairiness.

Biology

Female lays 50 or more eggs, which hatch in 4 to 9 days. Nymphs possess 4 moulting and pupate for 1 week. Pupation takes place in the soil. This stage lasts for 2-4 days. Adult (Fig 4.5) has the life span of 2 to 4 weeks. They have 5 to 8 generations per year (Saleem and Shah 2010).

Damage

Thrips feed on leaves and buds and also cause symptom of leaf deformation. Heavily infested seedlings appeared distorted. Cool season in June may cause severity in attack due to thrips especially on tip portions and squares. Leaves may show silvery appearance and become cup shaped in appearance. Heavy infestation may cause up to 37.6% loss of yield (Attique and Ahmad 1990).

Management

Cultural control

Thrips hibernates in plant debris, cultivated or cultured soil, tree depressions and on perennial weeds. In early sown cotton its appearance in April causes prominent yield loss (Ioan et al. 1978). Destruction of alternate host plant is also a good cultural practice for effective management of thrips (Bayer 2013).

Chemical control

Thrips ETL is 8 to 10 adults or nymphs per leaf. The important pesticides for the effective control of thrips are Cypermethrin + profenophos 440 EC (1500 mlha-1), Deltamethrin + Triazophos 360 EC (1200 ml ha^{-1}), Lambda-Cyhalothrin 2.5 EC (800 ml ha^{-1}), Profenofos 500 EC (2000 ml ha^{-1}), Thiamethoxam 25 WG (60 g ha^{-1}), Diafenthuron 500 SC (500 ml ha^{-1}). In addition, Acephate (Orthene 97) at the rate of 7.5 oz ha^{-1} is regarded as comparatively safer and suitable insecticides against this pest.

4.2.6. Cotton Aphid

Technical Name: *Aphis gossypii* Glover

Family: Aphididae

Order: Homoptera

Fig. 4.6 Cotton aphid, *Aphis gossypii* G. (Reproduced with permission by: http://www.invasive.org)

Identification

Aphid (Fig 4.6) has vast variations in size, colour and morphological forms (winged or wingless). Wingless aphids may vary from yellow to green to almost black in colour. Nymphs going to alate are covered with waxy materials and colour changes greenish blue to blue.

Biology

Aphids increase their generations both by means of parthenogenesis as well as by viviparity. Female may produce 22 nymphs in a single day. Eggs lay in winter season, hatch in spring time and nymphal stages lasts for 7 to 10 days with possession of 4 instars. They are mostly active from March till November with different number of generations per year. They hibernate in egg forms during extreme climatic conditions (Saleem and Shah 2010).

Damage

Aphid are considered under the category of major insect pests due to direct damage by sap sucking and indirect damage by sooty mold fungus and virus transmission to plants (Hollingsworth et al. 1994). Different aphid forms can cause different losses and attack outbreaks. Minute yellowish aphid has slow developmental periods with least fecundity so they are less important to lead a significant crop loss. While large green or black aphids have high reproduction rates with good development in less time and can cause more aphid population explosions.

Heavy infestation at seedling stage cause crinkling of the leaves, leaf falling and stunting of newly emerged plants. Honey dew is another source of infection inducing fungus. Aphid numbers (less than 25per leaf) are insignificant in producing visible damage while aphid number (more than 50 per leaf) can cause reduction of boll size, reduced plant growth with enhanced squares and bolls shedding. The most crucial stage of sensitivity of cotton against aphid is ranged from opening of the first boll till crop harvesting. On the boll maturing and lint forming stage of cotton in late season, aphids also cause qualitative loss to the lint by placing sticky honey dews on the lint of open bolls (Ahmad and Arif 2008).

Management

Cultural control

The early sowing of cotton, reduced irrigation and well managed fertilizer applications are important control measures to reduce aphid infestation. In addition, the development of resistant varieties and removal of alternate host can also be effective against this pest.

Biological control

Parasitic wasps such as *Lysiphlebustes taceipes*are (Cresson) are effective biocontrol agents of aphids. Lady bird beetles and syrphid flies also revealed good control. Fungus species (*Entomophthora* sp.) is also assisting in aphid control.

Chemical control

Aphids have developed high level of resistance against pyrethroids groups of insecticides giving least control in Pakistan (Ahmad et al. 2003). Less insertion of the insecticide via cuticle is considered to be important factor for least efficacy of organophosphorus and carbamates against aphids (Sun et al. 1987; Gubran et al. 1992). Chemical control comprises of Acetamiprid 70 WP (1.5 oz ha^{-1}), Thiamethoxam 40 WG (5 oz ha^{-1}), Pymetrozine (8 oz ha^{-1}) and Oxamyl Vydate C-LV (30 fl oz ha^{-1}). Pymetrozine 50 WG (150 g ha^{-1}), Thiamethoxam 25 WG (60 g ha^{-1}), Diafenthuron 500 SC (500 ml ha^{-1}), Profenofos + Cypermethrin 440 EC (1500 ml ha^{-1}) can also be applied.

4.2.7. American Bollworm

Technical Name: *Helicoverpa armigera* Hubner

Family: Noctuidae

Order: Lepidoptera

Fig. 4.7 American bollworm, *Helicoverpa armigera* H. (Photo credit: A. Nawaz, UAF)

Identification

Newly laid eggs are pale white, ribbed and domed shaped. Pale brown eggs turns dark brown one day before hatching. They adopt dark brown colour prior to hatching mainly due to dark headed larvae appearance. Occurrence of American bollworm on cotton was first time reported in 1967 in Pakistan. Then, infestation was reported on large scale in 1977 with successive increment in 1983, 1990, and 1994. The ABW has around 115 host plants including both wild and cultivated plant species.

Biology

A female moth laid 160 to 1500 eggs (450 eggs on average basis) during the whole life. Eggs are laid on upper leaf surface and top growing points of dark green plants (comprising square too) in an isolated or single way from 9 pm to 11 pm half night. Eggs are hatched in 2 to 5 days depending on the environmental conditions. The female prefers egg laying in top (75 %), middle (20%) and remaining descended parts (10%) of the cotton plant. Larva occupied 6 instars and is 35 to 42 mm in length. Larval stage is accomplished in 15 to 30 days in mild weather. Pupation occurred on soil surface or underneath (in 2.5 to 17.5 cm deep tunnel) depending on soil porosity and structure (Attique et al. 2000). Pupa has dark brown colour with 14 to 18 mm length. Emergence of adult occurs in 5 to 8 days (summer time) or may take 50 to 90 days (winter time). Adult insect (Fig. 4.7) has brown front wings with minute spots and bean shape spots on the ventral surface of the fore wing near the base. Hind wings are white with black spots chucks on the posterior margins. Female is larger than the male both in size and wing expansion (Fig. 4.5).

Damage

Insect is very devastating in nature. This can be assessed from the fact that advanced countries like USA has included it in the list of quarantine pests. Larva feed voraciously on buds, squares and flowers. Squares are fall off in severe larval infestation. When flowers are attacked, they fail to form boll because both carpals and stamens have been eaten by the larvae. When bolls are formed, they are depleted from qualitative seeds due to heavy inside boll phaging. A basic difference on boll damage by *Helicoverpa armigera* H. than other bollworms is larger boring hole with extensive excretions of waste outside the hole.

Management

Cultural control

All damaged plants should be removed from the fields along with host weeds. Before sowing, deep ploughing should be done to expose hidden pupae to natural enemies and drastic climate. Hand picking and destruction of infected bolls may also be practiced on small scale.

Chemical control

Chemical control should only be practiced when ETL (5 brown eggs or 3 neonate larvae or both when 5 in numbers on 25 plants) has reached. Application of Profenofos 500 EC (2000 ml ha^{-1}), Lambda-Cyhalothrin 2.5 EC (800 ml ha^{-1}), lufenuron 50 EC (2000 ml ha^{-1}), Emamectin benzoate 19 EC (1200 ml ha^{-1}) give effective outcomes of control. It is also precisely managed with Deltamethrin and Triazophos mixture (Deltaphos 360 EC) possessing good egg and larvae killing ability at the rate of 1500 ml ha^{-1} and 1600 ml ha^{-1} respectively. Some other insecticides including Spinosad 240 SC (250 ml ha^{-1}) and Indoxacarb 150 EC (175 ml ha^{-1}) foliar spray can also be used.

4.2.8. Pink bollworm

Technical Name: *Pectinophora gossypiella* Saunders

Family: Gelechidae

Order: Lepidoptera

Fig. 4.8 Pink bollworm, *Pectinophora gossypiella* S. (Photo credit: A. Nawaz, UAF)

Identification

In Pakistan, the existence of this insect as pest was observed in 1961 due to wide sowing of upland cotton in southern Punjab. The pink bollworm is known to have 70 host plants (Noble 1969).

Eggs are laid on leaves, younger shoots, squares and young bolls in groups (2-4 eggs) whitish and flat in appearance. Larva has shiny white colour initially with later adoption of pink colour. The last instar shows a reddish pink pattern. Pupa is of reddish brown colour wrapped in a silken cocoon. Its moth is dark brown in colour (Fig. 4.8) with the wing span of 8 to 9 mm. Forewings have black spots with deep fringes on the hind wing margins.

Biology

Female moth lays 200 to 400 eggs in 2 to 4 aggregations. Pink bollworm larvae have 4 moults and hence 5 instars. The larval period lasts for 15 days. Prior to pupation, larva spin a silken cocoon around under the leaf debris mainly on top 5 cm of soil. Pupation to inclusions time is of about 7 days. Many larvae hibernate in double seeds by cutting and joining two seeds with oral secretions. Adult emerge after 1 week by rupturing puparial case. From October to November, this pest can complete 4 to 6 generations. The final life history of the insect is much of long duration oriented occupying 5 to 10 months. However, in non-hibernating or active time this whole cycle is accomplished in 3 to 4 weeks with high number of generations in that time (Panwar 1979).

Damage

First generation PBW appear in April. They stick the petals together to produce rosette form. Infestations of buds due to larvae damage buds. Further invasive symptoms lead to the opening of the bolls prior to ripening. Intractable attack cause 85% infestation while 87% devastation of bolls has been also reported (Panwar 1979). PBW damage can only be seen through boll dissection. It also feeds on seed which release oil to stain the lint with yellowish dirty colour hence fetching low price in market. More frequency of rain distribution in the months of August and September consequently cause more boll infestation.

Management

Cultural control

Double seeds containing hibernating larvae must be removed prior to sowing. Seeds should be exposed to sunshine for adequate period to kill any harmful insect present in them. Deep ploughing should be done to expose hidden hibernating insects to natural enemies and climate.

Biological control

Biologically *Trichogramma* spp. served as good egg parasite and *Eulopid* sp. is a better parasitoid of its pupae. Eggs and neonates are actively controlled by *Anthocorid* bug *Triphlestantilus* (Panwar 1979).

Chemical control

The ETL is 5 larvae PBW on 100 bolls (i.e., 5% damage). It is not feeding on other plants except cotton; hence, cotton cultivation manipulation can control this pest to a wide manner. However, now it is also reported on Okra as well. Outer chemical spray is not helpful completely to control this pest because it spends most of its life span inside the bolls. So, in such a situation, insecticides with translaminar (having residual action up to inner side of boll) and contact efficacy are desired, e.g., Deltaphos (Deltamethrin and Triazophos) at the rate of 1600 mlha-1. Spray of Profenofos 500 EC (2000 mlha-1), Lambda-Cyhalothrin 2.5 EC (800 mlha-1) is also helpful. Cypermethrin 10 EC (1200 mlha-1), permethrin 25 EC (1000 mlha-1) and fenvalerate 20 EC (600 mlha-1) can also be employed effectivel (Panwar 1979).

4.2.9. Spiny bollworm and Spotted bollworm

Technical Name: *Earias insulana* Boisduval, *Earias vittella* Fabricius

Family: Noctuidae

Order: Lepidotera

Identification

Fresh eggs are blue in colour with ridges, later changing to bluish green to brown prior to larvae emergence. Neonate is light yellowish brown in appearance with black dots on the body with the length of 1.3 to 2.5 mm (Shah *et al*. 2014). *E. insulana* B. larvae have pale white or cream colour with well distinct finger like projections and orange spots. *E. vittella* F. (Fig. 4.9) is brownish with a white central length wise streak and is without finger like projections (Panwar 1979). Full feed larvae (3rd and 4th instars) are yellowish green to dark orange with body length of 7 to 14 mm. Both of *Earias* spp. has the approximately same body length. *E. insulana* B. pupae are of brown colour wrapped in knitted cocoon of greyish white silken material (Shah et al. 2014). Cocoon of *E. vittella* F. is white to creamy brown in colour (Al-Mehmmady 2000).

Adult moth of spiny bollworm is pygmy grassy green with comparatively small size when compared with spotted bollworm moth. Female is larger in size with abdominal tuft of hairs for egg protection after oviposition (Shah et al. 2014). A typical sign of identification between two species of *Earias* genus is that *E. insulana* B. moth has forewing completely green while *E. vittella* F. possess only a band of green line along the front wings (Panwar 1979).

Biology

After emerging from the eggs, adult prepare themselves for copulation with time elapsing of 2 to 3 days. Ovipositional time takes 6-8 days to complete. Females lay eggs in isolated form and not in cluster with the varying number of 70 to145 eggs in the complete life (Shah et al. 2014). But egg numbers may vary to 112 and 200 (Al-Mehmmady 2000). The whole life cycle of this insect pest is completed in 51.5 to 53.5 days with temperature range of 27±1ºC. Incubation duration is 4.5 days with the occupation of larval time period ranged to 17 days. Insect passes from 4 larval instars to attain pupae form. Pupation occurs in litter or leaf decayed material (debris) (Shah et al. 2014).

Pupal stage lasts for 16 days. Adult longevity varies for male (14 days) and female (16 days). Female has larger wingspan (10-11.5 mm) than that of male (7.3-10 mm). Moth possessed usually 13 generations in a year at 28.65 ± 0.98°C and 60.51 ± 0.9% of climatic requirements (Al-Mehmmady 2000).

Fig. 4.9 Spotted bollworm, *Earias insulana* F. (Photo credit: S. Zahid, UAF)

Damage

Being polyphagous in nature its abundance is out of control (Shah et al. 2014). Optimum infestation and invasion exists during the months of August and September (Syed et al. 2011). These can cause the devastation of 3.8 to 12.6% (Leghari and Kalroo 2002). Larvae of first moult prefer feeding on flowers, square and early buds (Shah et al. 2014). A single larva can damage many bolls and buds in its life period and initially attacked on growing points and then invade square, buds and flowers (Syed et al. 2011). Growing tips may be withered or dried. Boll boring due to larvae causes significant lint yield reduction both in qualitative and quantitative manners (Shah et al. 2014). When the bracteoles of the buds are destroyed, they become open forming a state referred as flared squares. 30 to 40 percent of fruiting bodies loss has also been observed. Total loss may reach 50% (Panwar 1979).

Management

Cultural control

All stray plants should be removed from the fields along with host weeds. Deep ploughing should be done to expose hidden inset forms to natural enemies and harsh climate (Shah et al. 2014).

Biological control

Larval and pupal forms can easily be managed by *Bracon* spp. and *Chilonus* sp. respectively (Shah et al. 2014).

Chemical control

ETL of these larvae is very crucial to the application of insecticides. No insecticides are need until insect pest has attained the status up to economic threshold level. ETL of *Earias* spp. is 3-5 larvae on 25 plants. These bollworms can be managed properly at the life regimes of egg to second larval instars with relative mortality of 10 to 6% (Shah et al. 2014). Later stages are difficult to control due to thick cuticle and hence hindrance in insecticide penetration. Lambda-Cyhalothrin and Cypermethrin are in most influential in the control of infestation and population reduction of larvae (Zidan et al. 2012). Spinosad 240 SC (200 mlha-1) and indoxacarb 150 EC (400 mlha-1) foliar spray can be utilized. Larvin 80 DF (1 kg ha-1) is also helpful.

4.2.10. Cotton Armyworm or Cotton Cutworm

Technical Name: *Spodoptera litura* Fabricius

Family: Noctuidae

Order: Lepidoptera

Identification

Eggs are oval and muddy white in appearance. Head of first instar is more in width while compared to the other successive instars having less width of the head than the rest of cylindrical body. Neonate is somewhat white in colour with yellowish green colour of the body along with green, yellow and reddish streaks running longitudinally on the body length after passing of about 60 minutes. With the age of larvae brown colour becomes more significant with 3 yellowish lines on body. Female is pale brown in colour with the exception of male having darker colour. Female possess bulky abdomen while the male has a tapered abdomen toward the end tip area (Fig. 4.10) (Cardona et al. 2007).

Biology

Armyworm being polyphagous in nature feeds on several plant hosts associated with 40 plant families (Brown and Dewhurst 1975; Holloway 1989). Eggs are laid in group masses of 2 to 3 layers on the lower leaf surface near the petiole. There may be about 870 eggs in one egg mass. Eggs of the insects retained themselves for the period of about 5 days with the larval duration of 25 days. There are 5 instars till pupa. Pupation takes place in the soil and pupal stage lasts for about 19 to 20 days till adult emergence (Fig. 4.6). Male longevity lasts for 5 to 10 days while female has the life span of 7 to 16 days (Cardona et al. 2007).

Damage

The first instar larvae isolate the veins of the leaves during their feeding whereas later instar larvae feed the whole lamina including veins. Young larvae exhibit feeding behaviour by scratching leaf surface. Mature caterpillars may form regular holes with skeletonize network of veins only with the leaf body. Larvae possess the capability devastate the crop with strong mandibulate mouth parts by chewing the leaves of cotton plants to an unlimited extent. Faeces of larvae are also another source of problem and quality reduction of the produce (Cardona et al. 2007).

Fig. 4.10 Armyworm, *Spodoptera litura* F. (Photo credit: S. Zahid, UAF)

Management

Chemical control

Chemical control is widely practiced against this notorious pest but conventional chemical of known importance failed to perform their management functions due to resistance build up in insect (Ahmad et al. 2007; Kranthi et al. 2001). Individuals of armyworm existing in Pakistan are more tolerant to insecticidal groups such as carbamates, organophosphates, pyrethroids, organocholrine with the inclusion of spinosad, indoxacarb, avermectinsetc (i.e., the new chemistry insecticides) (Ahmad et al. 2007; Ahmad et al. 2008). Profenofos 500 EC (800-1000 ml/acre), Lambda-Cyhalothrin 2.5 EC (330 ml/acre), lufenuron 50 EC (800ml/acre), Emamectin benzoate 19 EC (500 ml/acre) can also be used. Armyworm attack in patches and should be controlled with localized applications on relevant insecticides).

4.3. Wheat

4.3.1. Pink wheat borer (PWB)

Technical Name: *Sesamia inference* Walker

Family: Noctuidae

Order: Lepidoptera

Identification

Eggs are pale to creamy white in colour and turn to brown colour before hatching. Adults (Fig. 4.11) are small, stout and straw coloured in appearance. Hinder wings are of white colour. Larvae are of pinkish colour without strips and red brown head with cylindrical body (Saleem and Shah 2010).

Fig. 4.11 Pink wheat borer, *Sesamia inference* W. (Reproduced with permission by: http://www.invasive.org

Biology

The eggs are laid in groups in many rows within the leave sheath. The eggs are rounded, pale, creamy and yellowish green in appearance. There are about 4-6 generations in a year. The larvae bore and feed on stem tissues. It pupates inside the stem. The egg stage lasts for 7-10 days, larvae for 20-30 days and pupae for 8-10 days. The total life span is about 40-70 days depending upon the weather conditions.

Damage

PWB is newly emerging insect pest of wheat and mainly observed in wheat-rice cropping system. The damage is caused by the caterpillars in wheat crop. The caterpillars bore into the stem and destroyed the tissues of the central stem or aerial areas of the plant. The attacked plant produces dead heart or white ear heads or white ear spikes.

Management

Cultural control

The uprooting and destruction of infested wheat crop and removal of stubbles after harvesting can minimise the impact of this pest damage. In addition, the rotation of crops can also play a role in the breakdown of life cycle of the pest.

Biological control

The pupa is properly invaded and controlled by *Xanthopinpla* spp. and *Tetrastichus aygari* (T.). There are different egg (*Trichogramma minutum*) and larval (*Apanteles flavipes*, *Bracon chinensis*) parasitoids whose potential can be exploited for the management of this emerging pest.

Chemical control

Application of systemic insecticides should be preferred for the control of PWB. Pesticides like Quinalphos 25 EC (2000 ml ha^{-1}), Virtako 0.6 GR 10 kg ha^{-1}, Virtako 40 WG 100 g ha^{-1} could be effective pesticides against PWB.

4.3.2. Wheat aphid

Technical Name: *Sitobion avenae* Fabricius

	Rhopalosiphum padi Linnaeus
	Schizaphis graminum Rondani
Family:	Aphididae
Order:	Hemiptera

Fig. 4.12 Wheat aphid, *Sitobion avenae* F. (Reproduced with permission by: http://www.invasive.org)

Identification

It has been reported that different types of aphids (Fig.4.12) such as Bird cherry oat aphid (*Rhopalosiphum padi*), the English grain aphid (*Sitobion avenae*) and the green bug (*Schizaphis graminum*) are major threats to wheat in Pakistan (Shah et al. 2006). *R. padi* is medium sized olive coloured aphid with reddish-orange patches on back at base of cornicles. The other body parts such as antennae, eyes, legs and cornicles has black colour. *S. graminum* has small pear-shaped body with pale yellow to pale green colour. *S. avenae* has spindle-shaped medium-sized body and shows colour polymorphism. The body colour varies from green and brown. The black coloured antennae are shorter than body. The legs are yellow with dark tips of femora, tarsi and tibiae.

Biology

The eggs of *R. padi* are laid in small gaps between stem and axillary buds. The newly emerged nymphs star feeding on leaves and develop rapidly on fresh growth on plants. The nymphs feeding on fresh younger leaves develop to large wingless adults which give rise to winged generation. Winged population develops in response to overcrowding and poor nutrition which can migrate to other host plants. In addition, most of the aphids are attracted to yellow while *R. padi* is attracted to green colour (Schröder et al. 2014). English grain aphid overwinters both as nymphs and as eggs. In wheat, the aphids move to panicle when plants become mature. Winged population start in May and continue to develop throughout summer. Green bug (*S. avenae*) produces young ones with and without mating in cold winters and warm or mild climate conditions respectively. They complete 3 instars to become adult.

Damage

The aphids cause damage as nymph as well as adult. They aggregate on the leaves and shoots and initial stages of the crop and move to the ears and settle in the bracts and kernels near the maturity of the crop. The economic loss may increase up to 40%. They excrete honey dew from their bodies which acts as medium for the development of sooty mould fungus. Thus, they disturb the photosynthetic activity of the plants and ultimately reduce the yield.

Management

Cultural control

Delayed planting of wheat may avoid aphid's colonization before winter. Similarly, the weeds and stubbles of other crops which can become a source of feeding for aphids should be remove ad destroyed.

Biological control

The biocontrol agents that can have regulating effect on aphids are ladybird beetle (adults and larvae), flower fly larvae, lacewings, parasitic wasps, spiders and entomopathogenic fungi.

Chemical control

In Pakistan, wheat is used as staple food, there the use of toxic pesticides is not recommended. The pressure spray of hot water is very effective against aphids. Seed treatment of wheat with Thiamethoxam 70 WS (5 g /kg seed) is recommended to delay the aphid infestation on wheat crop. In addition, the uses of systemic insecticides are more effective than non-systemic ones against aphids.

4.3.3. Wheat armyworm

Technical Name: *Mythimana separata* Walker

Family: Noctuidae

Order: Lepidoptera

Identification

Eggs are spherical in shape with milky-white colour. Larva has black-brown and one intermediate light dorsal stripe and pupae are yellowish-brown and shiny colour. Forewings are greyish-yellow with while hind wings are grey with dark external margins. Forewings have a dark-grey or pale-reddish tint with reniform spots of distinct edges (Fig. 4.13).

Fig. 4.13 Wheat armyworm, *Mythimana separata* W. (Photo credit: A. Nawaz, UAF)

Biology

Adult life span is about 15-20 days. Female has the capacity to lay more than 300 eggs. The eggs laid in 2-4 rows in groups of 10 eggs per group. The development of eggs lasts for 4-12 days depending on environmental conditions. Larvae usually have 6 instars and pupate in the soil at the depth of 2 cm along the edges of fields and roads. They hibernate in soil as pupar during harsh weather conditions. The total development from egg to adult lasts for 30-45 days.

Damage

The caterpillars cause major damage at seedling stage of the crop. They move in the form of swarm from one field to the next. They feed upon of eaves and consume the ear heads. Thus, further growth of the plants ceased.

Management

Cultural control

During the initial stage of infestation, the uprooting and destruction of infested seedlings are recommended. Crop rotation is also important to breakdown the life cycle of the pest. Deep ploughing after crop harvest can expose the overwintering pupae to sunlight, birds and other natural enemies.

Biological control

Biocontrol agents utilizations includes the release of *Apanteles ruficrus* H., *Sarcophaga orientaloides* S. and *Exorista fallax* M. for the management of this pest. Sparrows and crows also act as predators, so the use of some material which can attract them in the field could casue very positive impact in population reduction of *M. separata*. The use of entomopathogenic fungi, *Beauveria bassiana* and *Isaria fumosorosea* can also be incorporated in pest populations as permanent mortality factors.

Chemical control

The use of systemic insecticides with 1st irrigation provides positive control of *M. separate* in wheat.

4.4. Rice

4.4.1. Rice stem borer

Technical Name: *Chilo suppressalis* Walker

Family: Crambidae

Order: Lepidoptera

Identification

The females lay scale like translucent-white eggs which turned dark-yellow before hatching. The young larvae are grayish-white with black head capsule which become lighter to brownish colour in later stages. The full grown larva is of dirty-white colour and taper slightly toward each end. They have 5 longitudinal stripes on dorsal side. Pupae are reddish-brown. The colour of adult forewings varies from dirty-white to yellow-brown sprinkled with gray-brown scales (Fig. 4.14). The hindwings white to yellowish-brown pure white (Bayer 2013; Vreden and Ahmadzabidi 1986).

Fig. 4.14 Rice stem borer, *Chilo suppressalis* W. (Photo credit: A. Nawaz, UAF)

Biology

This pest has 2-6 generation in a year depending upon the environmental and geographical condition. Female lays around 300 eggs in many batches during morning time. The developmental time for different life stages are 5-6 days (eggs), 25-30 days (larvae), 5-6 days (Pupa) and 6-7 days (Adults). Adults are nocturnal females generally live longer than males. The whole generation cycle continues for 35-70 days (Hill 1987; Bayer 2013).

Damage

This pest is present in all rice growing countries. The invasion symptoms vary based on the age of the rice crop. The young plants damage leads to the death of growing points and formation of typical dead heart. Heavy infestation can empty panicle formation. In Asia, 4-7% loss has been reported while 100% loss has been reported from individual fields in Japan (Cho et al. 2005).

Management

Cultural control

Removal of rice stubbles, destruction of alternate hosts of pests and proper irrigation and and chemigation is very essential for the management of this pest (Bayer 2013). Light traps are effective for both monitoring and control of essential for moth monitoring (Kim et al. 1988) of *C. suppressalis*.

Biological control

Trichogramma australicum and *Trichogramma japonicum* are important egg predators of *C. suppressalis* (Grist and Lever 1969). In addition, the development of transgenic crops expressing toxin genes from *Bacillus thuringiensis* is also effective against stem borers (Cheng et al. 1998)

Chemical control

Synthetic insecticide use for chemical control includes Virtako 0.6 GR, 10 kg ha^{-1}, Virtako 40 WG 100 g ha^{-1} and Lambda-Cyhaothrin 2.5 EC (500 ml ha^{-1}).

4.4.2. Yellow stem borer

Technical Name: *Scirpophaga incertulas* Walker

Family: Pyralidae

Order: Lepidoptera

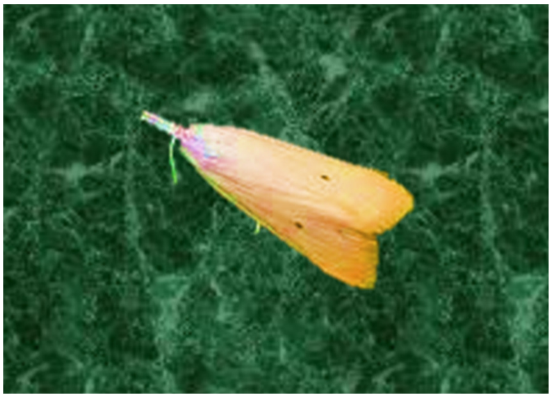

Fig. 4.15 Yellow stem borer of rice, *Scirpophaga incertulas* W. (Photo credit: A. Nawaz, UAF)

Identification

Yellow stem borer (Fig. 4.15) shows sexual dimorphism character but previously two genders of this insect were elaborated as different distinct species. The female has whitish yellow to creamy orange wings and a clear black knob like rather larger speck in the centre of the front wing. The wingspan of male and female is about 20-30 mm and 24-36 mm. Male has several minute sized, black dots at the tips front wings. Larvae are yellowish white in appearance and of about 20 mm in length with later turn greenish colour during diapause conditions (Bayer 2013).

Damage

S. incertulas attacks all stages (vegetative and panicle initiation) of the crop. Vegetative stage damage caused by larvae resulted in drying up of central shoot (dead heart) symptom. If the attack is at panicle initiation stage, then 'white ear' symptoms appear in which the unfilled panicles are developed. Each immature may cause destruction of wide number of plants and crop loss may increase from 20% to 60% in severe infestation.

Biology

The female moth lays 50-150 eggs in clusters and covered with brownish scales of female abdomen. Larvae hatch out within 5-10 days and complete 5 instars in 3-5 weeks. Pupation occurs inside the rice stem. Adults emerge from pupae 4-12 days normally in evening times and live for about 3-5 days. Life cycle may extend to 2-6 months depending on environmental conditions. This pest may complete 4-6 generations in overlapping forms per year (Bayer 2013).

Management

Cultural control

Destruction of stubbles after harvesting and the nursery planting after 20^{th} may give effective control of this pest.

Biological control

Different parasitoids have been reported in litreature but there is a need to exploit their potential to control this pest. Important parasitoids are *Cotesia flavipes* C., *Cotesia chilonis* M., *Xanthopimpla punctata* F. and *Stenobracon deesae* C., *Trichogramma australicum* and *Trichogramma japonicum* (Grist and Lever 1969).

Chemical control

Insecticide use for chemical control includes Virtako 0.6 GR 10 kg ha^{-1}, Virtako 40 WG 100 g ha^{-1}.

4.4.3. White stem borer of rice

Technical Name: *Scirpophaga innotata* Walker

Family: Pyralidae

Order: Lepidoptera

Identification

Eggs are off white in appearance and laid in cluster forms. Larvae are creamy white or yellowish in colour. The white pupae are enclosed in a silken cocoon and appear silky white. Adult moths (Fig. 4.16) are of white colour with orange cluster of abdominal hairs and black patch on each wing (Saleem and Shah 2010).

Fig. 4.16 White stem borer of rice, *Scirpophaga innotata* W. (Reproduced with permission by: http//www.nbair.res.in/insectpests/Scipophaga-innotata.php

Biology

This pest is active from April to November and complete 5-7 generations per year. The eggs incubation period is 4-9 days. The larval period is about 25-30 days after emergence from the egg. Pupal period lasts for 7-11 days and adult live for 4-14 days depending upon environmental conditions.

Damage

White stem borer is a causing devastation in rain fed areas of rice including irrigated zones. Ecological aspects are also helpful in determine pest number and so damage ratings. It can cause epidemics and destroy rice fields under favourable conditions. The 1st instar larvae may use silken threads to move to from one plant other plants. Larvae bore tillers and produces dead hearts in vegetative stage and white heads at generative stage of the rice plants.

Management

Cultural control

Removing of previous crop stubbles should be done with deep ploughing to destroy the hibernating pest. Proper planting spaces, suitable irrigations and adequate but not excessive fertilizer applications are important cultural control measures. In addition, closed plant spacing or direct seeding does not pest infestation, but does help to reduce yield loss due to white stem borer.

Biological control

Trichogramma australicum and *Trichogramma japonicum* are important egg parasitoids of this pest (Grist and Lever 1969). Egg parasitoids are more effective than larval or pupal parasitoids of white stem borer. The early application of insecticides should be avoided to egg parasitoid population build up in the field

Chemical control

Insecticide use for chemical control includes Virtako 0.6 GR 10 kg ha^{-1}, Virtako 40 WG 100 g ha^{-1} are effective to restrict the pest below ETL.

4.4.4. Green rice leaf hopper (GRPH)

Technical Name: *Nephotettix virescens* Distant

Family: Cicadellidae

Order: Hemiptera

Identification

Adults are bright green in colour while nymphs are more yellowish-green (Fig. 4.17). Male and female adults have some variation black coloration.

Biology

The biological studies of hoppers showed that each stage is host and cultivar dependent (Heong and Hardy 2009). Females oviposit in evening time and can lay up to 300 eggs in batches of 8-15 eggs. The nymphs hatch after 5-10 days and complete 5 instars in 2-3 week period before pupation. The whole cycle is of 4-5 weeks and they can have about 10 generations per year (Bayer 2013).

Fig. 4.17 Green rice leafhopper, *Nephotettix virescens* D. (Photo credit: A. Nawaz, UAF)

Damage

Both nymphs and adults suck the sap from phloem as well xylem of rice plants. In contrast to plant hopper, green leafhoppers do not cause hopper burn in crops. The initial sings of invasions are yellow, transparent patches that occur mainly on the leaf tops and along the mid-ribs of the leaves. The colour of hopper stages is dependent on host and cultivar on which they feed (Heong and Hardy 2009). Depositions of honeydew slowly occupy the plant surface, making a base for the growth of sooty moulds fungus. Losses are regarded due to viruses they transmit, especially tungro disease, which have irregular existence but can cause huge losses to the crop. Virus effected plants show several symptoms comprising stunted, malformed leaves, more tillering, undifferentiated cell clusters or gall formation and yellowing (Bayer 2013).

Management

Cultural control

On harvested fields, ratoon rice can serve as a resource of existence for leaf hopper and virus diseases. In addition, grass weed species may also harbour viruses. Therefore, sanitation in nursery and field crop is necessary to minimise pest/disease infestation

Biological control

The use of resistant varieties as part of an integrated control program is necessary for sustainable management of green leaf hopper. The entomopathgens (*Beauveria bassiana*) are also effective aginst *N. virescens* as permanent mortality factors in the field. In addition, the use of predators and parasitoids should be encouraged in the field to avoid insecticide resistance development in insects.

Chemical control

The development of resistance against insecticides in leaf hoppers is making their control more difficult (Long 2005). The important insecticides like Virtako 0.6 GR 10 kg ha^{-1}, Pymetrozine 50 WG 175-300 g ha^{-1}, Virtako 40 WG 100 g ha^{-1} are well known for its chemical control.

4.4.5. Brown plant hopper (BPH)

Technical Name: *Nilaparvata lugens* Stål

Family: Delphacidae

Order: Hemiptera

Fig. 4.18 Brown plant hopper, *Nilaparvata lugens* S. (Photo credit: A. Nawaz, UAF)

Identification

Adults are found in both macropterous (long-winged) and brachypterous (short-winged) conditions. These dimorphs of wings may be attributed to overcrowding during their developmental period or also food (Long 2005). The body appearance is brown and the wings are transparent white with very clear veins (Fig. 4.18). Young ones are white but they later slowly show darker colours in old age instars (Bayer 2013).

Biology

Macropterous forms migrate into rice fields shortly after transplanting. They colonize the new fields and produce young ones and most of the females develop as short-winged (brachypters) and males as long-winged (macropters). The adults mate one the day of emergence and females start egg laying on the following day. They lay around 300-350 eggs in groups of 5-15 eggs. But, short-winged females lay more eggs than long-winged females. The first instar nymphs hatch after 5-9 days and undergo 5 moults within 2-3 weeks. They have total adult life span of 10-30 days and produces 3-6 generations per crop.

Damage

Both nymphs and adults attack all stages of plant and suck the sap at the base of tillers by piercing-sucking mouthparts. Loss of nutrients and hinderance of conducting tubes causes plants to turn yellow and dry up rapidly. An enhanced population density of plant hoppers finally leads to hopper burn. This is also a vital vector of rice grassy stunt virus and rice ragged stunt virus (Chatterjee and Rao, 1997). In addition, they excrete honeydew and promote sooty mould development. BPH is also a vector of different viral diseases e.g., glassy stunt, ragged stunt, and wilted stunt.

Management

Cultural control

The excessive use of nitrogen fertilizer should be avoided and recommended doses should be used. Perform monitoring of BPH on regular bases after 30 days of transplanting the nursery. Similarly, alternate wetting and drying of field during infestation can also be effective to lower infestation or pest damage.

Biological control

The natural enemies of BPH like Wolf Spider (*Pardosa psuedoannulata*) and Lynx spider (*Oxyopes javanus*) can be used against both leaf-and plant hoppers. Similarly, Mirid bug, (*Cyrtorhinus lividipennis* Reuter) actively feed on nymphs and eggs of GRLH, BPH and WBPH (white-backed plant hopper).

Chemical control

Virtako 0.6 GR (10 kg ha^{-1}), Pymetrozine 50 WG (175-300 g ha^{-1}) and Virtako 40 WG (100 g ha^{-1}) are well known for its chemical control.

4.4.6. White-backed plant hopper

Technical Name: *Sogatella furcifera* (Horváth)

Family: Delphacidae

Order: Homoptera

Identification

The young nymphs are off white in colour. But with the passage of time, they develop prominent dark-gray and black patterns on their abdomens near maturity. Adults are yellowish brown to black in colour. They also have characteristic white spot on thoracic regions (Fig. 4.19).

Fig. 4.19 White-backed plant hopper, *Sogatella furcifera* H. (Photo credit: A. Nawaz, UAF)

Biology

WBPH males are all macropterous (long-winged) while females are present in both forms as macropterous (long-winged) and brachypterous (short-winged). The female has ability to lay 100-350 eggs which require 5-10 days for hatching. The nymphs start de-saping just after hatching at the plant base. They pass 5 nymphal stages (12-18 days) to become adults (4-10 days). There may be five generations of this insect per rice season.

Damage

Both nymphs and adults at the base of the rice plant and the leaf surface and cause direct (sap feeding) and indirect losses (sooty mould). The infested plants turn yellow. The WBPH infestation at panicle initiation stage of rice can decrease number of grains and panicle length. Damage of plant may be influenced by in such Plants which may possess less nitrogen constituents impacting the plant hoppers. Serious invasion of this pest may cause yellowing and then wilting of leaves (typically termed as hopper burn), with subsequent death of plants (Bayer 2013).

Management

Chemical control

Imidacloprid 70 WG (30 g ha^{-1}), Virtako 0.6 GR (10 kg ha^{-1}), Pymetrozine 50 WG (175-300 g ha^{-1}), Virtako 40 WG (100 g ha^{-1}) are effective chemicals against WBPH.

4.4.7. Rice leaf folder

Technical Name: *Cnaphalocrocis medinalis* Guenée

Family: Crambidae

Order: Lepidoptera

Identification

The eggs are oval shaped and creamy-white in colour. The immature forms (larvae) are light yellow to yellowish-green with dark brown heads and up to 25 mm in length turn into actively moving caterpillars. The body of the larvae turn green when starts feeding. The pupae are light brown and turns to reddish brown. The mature moths are shiny yellowish brown with dark-coloured inner and outer bands on both forewings (Fig. 4.20).

Fig. 4.20 Rice leaf folder, *Cnaphalocrocis medinalis* G. (Photo credit: Kamran, UAF)

Biology

Each female rice leaf folder oviposits about 300 disc-shaped eggs in an isolated fashion, usually near the top of a leaf. The immature appears after 4-6 days and complete 5 instars in 3-4 weeks. They stay in pupal stage for 6-10 days depending on environmental conditions (Kumar et al. 2009). This pest is found active throughout the rice growing season but most abundantly during rainy season as it prefers high humidity. The moths are nocturnal and active during nigh time (Bayer 2013).

Damage

During heavy infestation of this pest, the rice plants dries up and appear scorched. The larvae fold the leaves longitudinally before feeding and fasten the margins of infested leave through threadlike saliva. Then it starts feeding by scraping the green mesophyll within the folded leaves and continues feeding from one plant to another. This cause pale white strips appearance on the leaves. Therefore, the photosynthetic ability of rice plants reduced and damaged leaves act as entry points for bacterial and fungal infection. This pest cause maximum damage due to feeding on flag leaf of the plant.

Management

Cultural control

Avoid excessive use of nitrogen fertilizer. Removal of grassy weeds from the surroundings and rice field can help to prevent the population build-up of RLF on alternate hosts. The use of light traps to attract and kill the adults will help to reduce the population of next generations of RLF.

Biological control

Frogs and toads are very active predators of RLF. Trichogramma spp. and other natural enemies like lady bird beetles etc normally helpful to push the RLF below ETL.

Chemical control

The use of microbial insecticides particularly *Bacillus thuringiensis* provide effective control against RLF larvae. The pesticides like Deltamethrin 2.5 EC (400 ml ha^{-1}), Deltaphos 36 EC (1000 ml ha^{-1}), Virtako 0.6 GR (10 kg ha^{-1}), lambda-cyhaothrin (500 ml ha^{-1}) are effective against RLF.

4.5. Sugarcane

4.5.1. Sugarcane root borer

Technical Name:	*Emmalocera depresella* Swinhoe
Family:	Pyralididae
Order:	Lepidoptera

Fig. 4.21 Sugarcane root borer, *Emmalocera depresella* S. (Photo by: S. Zahid, UAF)

Identification

The female lays scale like and creamy white eggs. Full grown larvae are pale to creamy white in colour with yellowish brown head and slight creases on the body. Adults are yellowish brown with pure white hind wings (Fig. 4.21).

Biology

Root borers are normally active from April to October. They hibernate in stubbles in the form of larvae during winter season. The female lays 277-355 eggs singly on leaves, stems or on land. Incubation period is 5 to 8 days. Newly emerged larvae take entrance to the sugarcane plant body area by making holes in the underground cane internode (Cheema 1950). The five larval instars completed in 25-30 days while pupal time period is about 9-14 days. Adults emerge from pupae after 2-3 weeks and live for 5-7 days. The complete life cycle (egg-adult) occupies 54-68 days (Sardana 1997).

Damage

Newly hatched larvae bore inside stem area from the inner side of ground. They damage the central whorl of plants to form dead hearts and make them difficult to pull out. Plants may die in severe infestation at the initial stage or prior to cane formations. Positive relation between root borer infestation and wilt disease spread by *Fusarium moniliforme* S. were found but not present in all cases (Sardana et al. 2000). Mature plants exhibit minimum tillering ability decreased sugar contents (Cheema 1950; Bhatt et al. 1996). This pest can cause 1.3-10% loss Infestation is normally enhanced in well irrigated, sandy or sandy loam soils (Sardana 1993, 1996).

Management

Cultural control

The use of healthy seed helps greatly in pest population reduction on later crop stages. The fertilizer application with recommended doses minimise the pest infestation as well.

Mechanical control

Use of light traps and field flooding is also a better integrative pest reduction measures (Sardana 2000).

Biological control

Apanteles wasps (*Apanteles flavipes* C.), *Trichogramma chilonis* I. and Stenobracon sp. are its natural parasites. Larvae of borers are not controlled easily by insecticides due to their internal presence. The cultural and biological control measures seemed to be efficient ones (Huffaker 1980). *Trichogramma chilonis* I. can efficiently manage the insect pests of borers including top borer at a rate of 15000 to 30000 parasites released in one acre ((Khan and Alam 2001).

Chemical control

Confidor at 0.5 kg a.i ha^{-1} and Curaterr 3G or Sevidol 4:4 at 25 kg ha^{-1} caused good management of the root borer *E. depressella* and the shoot borer *Chilo infuscatellus* S. (Khan and Jan 1994). The fungi *Beauveria bassiana* B. and *Metarhizium anisopliae* M. are good control agents for hibernating larvae (Sardana 1996).

4.5.2. Sugarcane stem borer

Technical Name: *Chilo infuscatellus* Snellen

Family: Crambidae

Order: Lepidoptera

Identification

Eggs are creamy white and scale like in shape. The full grown larvae are 20-25 mm in length with muddy or smudge white colour. It has five light coloured longitudinal lines on the body. Moths have pale brown front wings and cream colour to white hind wings (Fig. 4.22) (Arain 1981).

Fig. 4.22 Sugarcane stem borer, *Chilo infuscatellus* S. (Photo by: S. Zahid, UAF)

Biology

The full developed larvae hibernate in stubbles of previous crop. Female moth oviposits 300-400 eggs in group of 11-36 eggs lower surface of leaves. Larvae hatch out in 4-5 days. They pass the 5 instars in 21-28 days of development. Pupae period lasts for 6-7 days in prior constructed pupal chamber with an exit hole by the larvae. Moths have the life span of 2-4 days. The shoot borer complete 4-5 generations in a year (Arain 1981).

Damage

The stem borer genus *Chilo* contains 41 species. Eggs hatch in 5 days and larva cuts a hole in the stem above ground level. They enter the central shoot and feeds from inside. A demise of 10-20% plants from early to later season. Caterpillar produces a series of minute holes and damages to the plants. After the formation of canes, the larvae attack on intermodal area and make dead heart. The economic threshold level of this pest is around 15% crop infestationp (Panwar 1979). It can cause up to 36.51% loss in the field (Aheer et al. 1994).

Management

Cultural control

The use of healthy and pest free seed helps in pest population reduction on later crop stages. Remove and destroy dead shoots to destroy the hibernating individuals.

Mechanical control

Use of light traps and field flooding is also a better integrative pest reduction measures.

Biological control

Increased utilization of pesticides harms the beneficial fauna causing in at once break up of insect pest population with other toxicity hazards, hence bio-control agents are good measures against insect pests. *Trichogramma chilonis* I. can properly control the insect pests of borers including top borer at a rate of 15000 to 30000 parasites placed per acre (Khan and Alam 2001). These parasitoides effectively decrease the level and percentage of borer infestations from 16.2 % to 4.2 % (Ashraf et al. 1995).

Chemical control

Soil application of carbofuran at 33 kg ha^{-1} or phorate 10G at 25kg ha^{-1} can reduce pest infestation to significant level. Application of Curaterr 3G or Sevidol 4:4 at 25 kg ha^{-1} caused good management of the shoot borer (Khan and Jan 1994).

4.5.3. Gurdaspur borer

Technical Name: *Acigon steniella* (Hampson)

Family: Crambidae

Order: Lepidoptera

Fig. 4.23 Gurdaspur borer, *Acigon steniella* H. (Photo credit: S. Zahid, UAF)

Identification

The females lay flat shaped scale like eggs in clusters. Full size larvae are creamy white with orange brown head area. The larvae are creamy white in colour with orange brown head. Each larva has 4 violet colour prominent longitudinal stripes on the body. Moth has dark brown colour with different number of dark colour dots on the external margin of front wings. Hind wings possess white colour (Fig. 4.23). The life span of adult moths is 4-5 days. Life cycle is completed in 35-40 days. The pupal stage lasts 6-12 days Adult moths

Biology

Female moth lays 90 to 300 flat eggs in cluster form and placed near to mid veins of the leaves. The incubation period lasts for 4-9 days. Newly hatched larvae enter the top portion of sugarcane through a single hole just above the node. Before pupation, larvae complete 5 instars within 20-27 days and remain in pupa form for 6-12 days. Life cycle is completed in 35-40 days and there are 2-3 generations per year.

Damage

The larvae feed internally by forming zig zag or curling galleries inside the cane. Wither tips or dried leave aggregations are also appeared. Loss may increase upto

20-25% with more range to 70-75% in sever infestation. A quantitative loss of 29% sucrose, 17% total solids and an increment of 84% glucose content is recorded because of borer attacks.

Management

Cultural control

During harvest or seed selection, collection and removal of damaged canes helps in pest population reduction on later crop stages.

Mechanical control

The capturing and killing of adult moths by using light traps from field can minimise the pest attack in the next year.

Biological control

Increased utilization of pesticides harms the beneficial fauna and other non-target organisms. The bio-control agents (predators, parasitoids ans entomopathgoens) are good measures against insect pests. *Trichogramm* spp. has the capability to reduce the level and percentage of borer infestations when released sufficient amount of parasitoid populations (Ashraf et al. 1995).

4.5.4. Sugarcane top borer

Technical Name: *Scirpophaga nivella* Fabricius

Family: Crambidae

Order: Lepidoptera

Fig. 4.24 Sugarcane top borer, *Scirpophaga nivella* F. (Photo by: S. Zahid, UAF)

Identification

A pure white adult female moth with small or intermediate in size and have orange anal tuft of hairs. Sometimes female has brownish tuft if hairs (Fig. 4.24). Male adult has silvery white fore wings. Full grown larva is creamy white in colour. The difference between male and female moth is the abdominal cluster of hairs at the tip (Mandal and Jha 2008).

Biology

The adult female lays around 150 eggs in the form of cluster. Each cluster has 30-60 eggs which are covered with abdominal tuft of hairs on the lower leaf surface. The pest hibernates as larva in the stubbles of sugarcane crop. Eggs incubation period lasts for 5-7 days. The larval life span is around 4 to 5 weeks. The larvae complete 5 instars before pupation. After 7-9 days of pupation, adult moth emerges by making an exit hole from the pupal case. This is multivotine pest and complete 4-5 generations in a year (Kumar and Rana 2012).

Damage

The caterpillars start feeding through boring the midrib and making red markings with small holes in the leaves. Gradually, larvae feed towards the upper portion of the plant and cause dead heart symptomes. As a result, side branches start growing from the lower nodes of the plant and causing bunchy top characteristic of the plant. Sugar recovery may fall in the limits of 0.2-4.1 units (Panwar 1979). It decreases the yield of sugarcane by 36-56% in severe infestation (Pandey et al. 1997). More lethal infestation has been reported from 3rd week of May to 1st first week of July (Deka and Sharma 2005).

Management

Cultural control

Collection and burning of stubbles can reduce the pest infestation. Furthermore, the use of healthy and insect free seed also has positive impact in pest management programs.

Biological control

Egg parasitism due to *Telenomus beneficiens* Z. is reported from 3-5% to 90% with area and climatic specifications. *Isotima javensis* R. is a good parasite of its larvae and pupae showing around 70% parasitism. Egg parasitoid *Trichogramma chilonis* I. can be managed the insect pests/ borers including top borer at a rate of 15000 to 30000 parasite released in one acre (Khan and Alam 2001).

Chemical control

In chemical control carbofuran 3 G and phorate 10 G (both at the rate of 25 kg ha^{-1}) are helpful in the control of pest in June to July (Panwar 1979).

4.5.5. Sugarcane pyrilla

Technical Name: *Pyrilla perpusilla* Walker

Family: Lophopidae

Order: Homoptera

Fig. 4.25 Sugarcane pyrilla, *Pyrilla perpusilla* W. (Photo credit: S. Zahid, UAF)

Identification

Females lay oval shaped and creamy white eggs arranged in 3 to 5 lines laid on the lower surface of the leaf. Nymphs are initially greenish and turn yellow or brownish colour with two white scaly feather resembled string or yarn (filaments) at the tip of the abdomen. They are wingless and have 5 nymphal instars. Adults are 7-8 mm long having snout bearing piercing and sucking mouth parts. Adult hoppers and breed throughout the year (Fig 4.25).

Biology

Female oviposit 300 to 536 eggs near the midrib in groups of about 20 eggs on the lower leaf surface (Summer) or inside the leaf sheath (Winter). Eggs are covered with abdominal white hairs or scales. Eggs hatch in 6-15 days or more depending on summer or winter season. Nymphs take 8 weeks to 6 months to complete development (Panwar 1979). Two polytypical species exists for this pest namely *P. perpusilla* W., widespread in Pakistan, India, Sri Lanka and Thailand and *P. aberrans* K. occurring in Sri Lanka and South India (Fennah 1963). There are 3 to 4 generations of leaf hopper per year.

Damage

This pest is active throughout the year and causes both qualitative and quantitative losses to the crop. They suck cell sap from the lower leaf surface of plants and cause yellowing and eventually drying infested leaves. The severe infestation can lead to 28% yield loss and 2-34% decrease in sucrose quantity. Poor growth of sugarcane setts is also reported (Kumarasinghe and Wratten 1996). Sooty mould is also another indirect damage caused by leaf hopper owe to honey dew excretions. A symbiont bacterium *Klebsiella* spp. in the mycetomes (Khan 1977) may also play role in crop damage.

Management

Cultural control

Ratoon crop should be avoided as it leads to pest establishment to horrible limits (Khan and Khan 1966). There are also suggestions for burning of all debris and cane stubbles after crop harvest for the destruction of egg clusters of this leaf hopper.

Biological control

Bio-control agents are good measures against insect pests. In Pakistan, 12 natural enemies of pyrilla have been recorded (Mohyuddin 1981). Its eggs are effectively parasitized by *Tetrastichus pyrillae* C., *Ageniaspis pyrillae* M. and *Cheiloneurus pyrillae* M. parasitoids. Nymphs are controlled by the parasites such as *Lestodryinus pyrillae*. Adults can be managed by *Epipyrops melanoleuca* F. predator. It has been reported that about 80% pest population can be managed with egg prasitoides of pyrilla and 20 % with its nymphal and adult predators and parasitoids (Chaudhary and Sharma 1988). Six species of pathogenic fungi are observed on *P. perpusilla* but *Metarhizium anisopliae* M. is the only pathogen used against pyrilla (Avasthy 1973; Asre et al. 1983).

Chemical control

Both contact and systemic pesticides can be applied efficiently for the management of *P. perpusilla*. The 0.5% pesticides (Malathion, Thiodon, Fenitrothion) application during early stages of the crop can be very effective. The chemigation of carbofuran 3 G and phorate 10 G (both at the rate of 25 kg ha^{-1}) are helpful against this pest.

4.5.6. Sugarcane black bug

Technical Name:	*Cavelerius excavates* Distant
Family:	Lygaeidae
Order:	Hemiptera

Fig. 4.26 Sugarcane black bug, *Cavelerius excavates* D. (Photo credit: S. Zahid, UAF)

Identification

The eggs are creamy white in colour. Adults have black body and white shiny wings with spots on them (Fig. 4.26). Nymphs are like adults but smaller in size. Body length of adults varies from 6-7 cm.

Biology

Female lays 55-478 eggs (depending on environmental conditions) in summer in the form of clusters of 14-67 eggs per cluster. The female bugs place the eggs in the inner leaf sheath for proper pre-birth care of young ones during summer season. While in winter season, eggs are laid in the soil to a depth of 5-7 cm. Eggs hatch in 9-17 days. Nymphs take 4-6 weeks to complete their development. This bug complete 3 generations in a year.

Damage

Both adult and nymphs cause damage due to sap feeding of plants. They are usually present under leaf sheath where these are congregated in groups (Panwar 1979). Cropping stage and time of plantations also played role in pest establishment. Broad and loosely attached leaf varieties are more susceptible and preferred to its invasion. The 46.41% pest infestation was observed in ratoon cropping of sugarcane (Zada et al. 2013). Damaged leaves appeared whitish to pale in colour with minute holes of feeding.

Management

Cultural control

Avoid ratoon cropping and burning of leaf debris could be effective to reduce infestation

Biological control

The predatory insect such as *Coccinella undicimpuntat* L., *Menochilus sexmaculatus* F., *Coccinella septumpunctata* L., and *Borumoides saturalis* F. showed significant reduction (64.06% to 43.81%) of bug infestation when released at the rate of 500 adults/month/plot without application of toxic pesticides (Zada et al. 2013). Eggs parasitiods (*Nardo cumaeus,* and *N. phaeax*) can also be sued for its management (Panwar 1979).

Chemical control

Application of pesticides (0.5 kg ha^{-1} or 500 m1 ha^{-1}) such as Acephate 75 SP or Dimethoate 30 EC or Malathion 50 EC on leaf whorls to target all stages of black bug (eggs, nymphs, adults) can effectively control this pest.

4.5.7. Termites or White ants

Technical Name: *Odontotermes obesus* (Rambur),

Family: Termitidae

Order: Isoptera

Identification

These are social insects with different caste systems comprise of primary reproductive castes-queen and king (queen with creamy or pale white abdomen with parallel dark brown strips along the abdomen (Fig. 4.27) (Panwar 1979). There are 5 species of *Odontotermes* and 2 species of Microtermes are observed from sugarcane field at Nowshehra and Charsadda Tehsils (Salihah et al. 1988). King has small body size than queen. The complimentary casts are winged or wingless forms of male and female termites and used for replacement of queen or king in case of their mortality.

The workers and soldiers are non-fertile termites with well-developed head and thoracic regions. Soldiers are further categorized into mandibulate (expel the enemy by finghting with them) nasute (defend the colony by sprinkling foul smelling and toxic secretions of rostrum on the invaders/enemies) forms. *O. besus* R. swarms in early monsoon whereas swarming of *O. asssumthi* takes place from June-July (Panwar 1979).

Fig. 4.27 Termites, *Odontotermes obesus* R. (Photo by: S. Zahid, UAF)

Biology

Queen is normally termed as egg laying machine because it can lay around 80000 eggs in one day. During summer season, eggs hatching time is 5-6 days then they needed 6 weeks to complete larval development or to take appearance of workers or soldiers. The workers are produced with fertilized eggs while soldiers are cropped up from non-fertilized eggs and normally remained stunted in their growth patterns. Workers are smaller in size than soldiers. Queen can live from 6-10 years. This life span can extend to 20 years but in rare cases. Both king and queen live in the royal chamber made of hard soil which is difficult to dig with spade (Panwar 1979).

Damage

Termites cause damage from planting till harvesting. The damage pattern and site of invasion are normally varied with rain times. Before rainy season, sugarcane setts and young seedlings are affected while tillers or developing canes are damaged after rainy season. Termite attack on germinating or early stages can cause 90-100% crop loss (Ahmed et al. 2008). Plants died leaving the dried shoot areas. Leaves in whorls show yellowing from outer to inner edge with ultimate drying and killing of sugarcane plants.

Management

For controlling the termites, a wide number of procedures and techniques have been used comprising chemical, cultural and biological methods.

Cultural control

Sunflower can be raised as intercrop in spring sugarcane crop without any harmful impacts (Bhullar et al. 2006). Similarly adding the organic matter in the soil assists in prohibiting loss due to termites (Mando et al. 1999). Use of healthy and insect pest free seed helps greatly in pest population reduction.

Biological control

The conclusion made by 50 years of research revealed that biological control has failed to show real promise for termite management (Chouvenc et al. 2011). But still there are potential candidates to be used as biocontrol agents against termites.

Chemical control

The use of chlorpyriphos 20 EC 400 g active ingredients per acre is helpful for management of termite infestation.

4.6. Maize

4.6.1. Maize stem borer (MSB)

Technical Name: *Chilo partellus* Swinhoe

Family: Crambidae

Order: Lepidoptera

Identification

Eggs are flat and oval (scale-like), creamy-white, about 0.8mm long. MSB larvae (caterpillars) are creamy-white to yellowish-brown in colour, with four purple-brown longitudinal. Moths are slender shape, shiny and light yellow-brown to dark red-brown in colour (Fig. 4.28). Hind wings of male moths are a pale straw-colour, and in females, they are white. Eggs are placed on the lower leaf surface near the mid rib (a very important aspect to see for egg destruction) in a group of 30 to 45 with emergence of neonates in about one week (Farag et al. 1992)

Fig. 4.28 Maize stem borer, *Chilo partellus* S. (Photo credit: A. Nawaz, UAF)

Biology

MSB biological parameters including damaging rates are greatly enhanced by reduced temperature and relative humidity (Panwar 1979). Eggs are laid in batches on leaf surfaces, usually close to the midrib. They hatch after 4-10 days. Young caterpillars initially feed in the leaf whorl. Older caterpillars tunnel into stems, eating out extensive galleries, within which they feed and grow for 2-3 weeks. When larvae are fully grown, they pupate and remain inside the maize stem. After 7-14 days adults emerge from pupae and come out of the stem. The MSB accomplished life cycle in 22-33 days and possess several generations in one year. Full feed larvae hibernate in October-November during the winter season (Farag et al. 1992).

Damage

Maize stem borer larvae feed in leaf funnels and cause small pin holes in lines in younger leaves and/or patches of transparent leaf epidermis (window panes) in older leaves. After entering the stem, they feed at the growing point causing dead central leaves and ultimately form a characteristic 'dead-heart', especially in young plants. The full grown larvae make tunnel in stems and in maize cobs. The tunnel in stem cause weakening of stems and they may break and lodge.

Management

Cultural control

Crop sanitation including the removal of crop residues and alternate host plant as well as volunteer crop plants reduces carryover of diapausing larvae to the next crop.

Biological control

C. partellus control by using parasitic wasps (*Cotesia flavipes* C. and *Xanthopimpla stemmator* T.) has shown good results. The use of entomopathgens is also effective. In addition, the development of transgenic maize can minimise the use of synthetic pesticides as happening in developed countries.

Chemical control

Applications of granular systemic insecticides or dusts to the leaf whorl early in crop growth to kill early larval instars are very effective. Seed treatments of the corn at earlier level can delay the attack of such pests. Chlorentranilipyrole + TMX 0.6 GR at the rate of 10 kg ha^{-1} can also give effective control of MSB.

4.6.2. Corn earworm

Technical Name: *Helicoverpa zea* Boddie

Faimly: Noctuidae

Order: Lepidopetra

Identification

Corn earworm moths are most active during evening and night. They are about 0.75-inch-long with a wing span of 1 to 1.5 inches. Adults range from olive green, to tan, to dark reddish brown in colour. Egg lying occurs throughout the sweet corn growing season. The tiny, white eggs are laid singly on the foliage and fresh corn silk. After about a day, eggs develop a reddish-brown ring in the top portion (Fig. 4.29).

Eggs are spherical with 12 or more ridges radiating from the top. Young larvae are greenish with black heads and conspicuous black hairs on the body. Fully developed worms are about 1.5 inches long and range in colour from pale green or pinkish to brown. Moth usually appears flying in spring season and pupae are their hibernation form. Inactive or diapause pupae can be seen in later crops of summer (DPIF 2005).

Fig. 4.29 Corn earworm, *Helicoverpa zea* B. (Photo credit: A. Nawaz, UAF)

Damage

Female moth placed eggs on the reproductive structures of the floral parts of host crop. After hatching, larval feeding on those parts causes economic losses to the crop (Reed and Pawar 1982). *Helicoverpa* larvae feed on 17 vegetable and agronomic crops but maize and sorghum were most preferred (Martin et al. 1976). The corn earworm may be present throughout the season but is most abundant during August and September. Larvae feed on leaves, tassels, the whorl, and within ears, but the ears are the preferred sites for corn earworm attack. It is vital note that 90% of all the damage and feeding is done by the third instar larvae with 50% larval food using in 5^{th} and 6^{th} instars. Ear damage is characterized by extensive excrement at the ear tip. Young larvae feed on corn silks, clipping them off. Shortly thereafter, they feed their way into the ear where they remain, feeding in the tip area until they exit to pupate in the soil.

Management

Corn earworm is primarily a problem in sweet corn where treatments should be timed to coincide with egg hatch. Use of IPM (Integrated Pest Management) and AWM (Area Wide Management) based methodologies are very beneficial for the control of corn earworm. In addition, it is also important to associate them with cultural, biological and mechanical means of pest control (DPIF 2005).

Biological control

Many predators and parasites attack corn earworm eggs, including several species of *Trichogramma.* Most parasitized eggs turn black, but there may be a lag period before they do so. General predators such as lacewings, minute pirate bugs, and damsel bugs feed on corn earworm eggs and small larvae. Lynx spider, predatory shield bug, nucleopolyhedrosis virus, fungi (Metarhizium, Numurea and Beuvaria) including ascovirus stunts are also helping as good biocontrol agents for corn earworm (DPIF 2005). In sweet corn, very early plantings require fewer treatments than late-season corn because earworm population densities increase as the season progresses.

Chemical control

Insecticidal control of corn earworm is difficult without proper monitoring of the crop. Plant volatile compounds of those serving as host are important management factor to be used in these pest management techniques via forecasting and monitoring the pest individuals (Tingle and Mitchell 1992; Udayagiri and Mason 1995). Biological and cultural controls and sprays of *Bacillus thuringiensis* and the Entrust formulation of spinosad are acceptable for use on an organically grown crop (Zalucki et al. 1986; Fitt and Boyan 1991). The presence of large numbers of eggs on fresh corn silks indicates the potential for damaging populations. Eggs hatch in 5 to 7 days following oviposition. Once larvae enter the corn ears, control with insecticides is difficult. Pheromones trap associated with species specify lures and sex pheromones are very helpful in moth detection and surveying of *Helicoverpa* (DPIF 2005)

4.6.3. Maize shoot fly

Technical Name:	*Atherigona soccata* Rondani
Family:	Muscidae
Order:	Diptera

Identification

The female lays white and elongated eggs. Larvae feed on the plant's growing point. Full grown larva is of white to pale yellow in appearance. This stage continues for 7 to 12 days. Pupation takes at the base of dead plants or in soil. Mature fly is of about 3-4 mm in length having grey-brown body with yellow colour abdomen and legs. The abdomen has dark spots.

Biology

Eggs are laid by female singly on the lower surface of leaf blades. Hatching take places after about 2-3 days or with longer time. This stage continues for 7 to 12 days. Pupation takes at the base of dead shoots of plants or in soil with the duration of 7 to 12 days. This pest can complete up to 10 generations annually and a single life-cycle (egg-to-adult) may take 3-6 weeks (Kundu and Kishore 1970).

Damage

This symptom of infestation is evident within 2-3 days after attack. The shoot fly is considered as one of the most important and destructive sorghum/maize pests. It feed on the growing points of the plant that may kill the central shoot and ultimately causing "deadheart". But, dead heart production is low and the appearance of resistance is long lasting in different seedling growth stages in resistant germplasm lines (Singh et al. 2004). The attack is maximum at seedling stage. Grain losses and yield decrease are in direct relation with the fly infestation (Rai and Jotwani 1977). Damage with respect to money loss may be assessed to 274 US million dollars in semi-arid tropical regions (ICRISAT 1992).

Management

Cultural control

During no cropping time, insect used alternate hosts for its survival (Sharma and Nwanze 1997). They must be removed.

Chemical control

Application of 10% Phorate granules in furrows before sowing @15kg ha^{-1} should be done and the insecticide should be covered with thin layer of soil after which seed should be sown. Thiamethoxam 70 WS at the rate of 3g kg^{-1} for seed treatment is effective. Ovipositon stimulant to deflect the fly to non-hosting crops for egg laying may also serve as good control (Unnithan and Saxena 1990).

4.6.4. 4.6.4. Corn aphid

Technical Name: *Schizaphis graminum* Rondani

Family: Aphididae

Order: Homoptera

Identification

Several species of aphids may be found in corn. Corn leaf aphids are small to medium and bluish green in colour. They also infest small grains. The green bug (*Schizaphis graminum*) is a moderate-sized aphid with light green abdomen having darker stripe down the middle. Both winged and wingless forms occur on corn plants. The pest population may increase in reduced temperature conditions (Barbiani 2003).

Biology

Aphids can increase their off springs both by sexual and asexual reproduction. In commonest reproduction mode, female give rise nymphs without producing eggs. Temperature and relative humidity levels effect the aphid population. The aphid can complete around 20 generations in a year. Mild temperature and humidity is favourable for its propagation (Zulfiqar et al. 2010).

Damage

Corn leaf aphid infestations usually start in the plant whorl. Heavy infestations may curl leaves and stunt the plant growth. Later infestations may completely cover the tassels and upper leaves. Corn leaf aphids excrete a sticky substance called honeydew, which accumulates on the plants. The honeydew eventually turns blackish as sooty moulds grow on it. Heavy amounts of sooty mould may be more damaging to silage corn than to corn for grain.

Green bugs and green peach aphids also infest corn, but usually do not build up to the high numbers of corn leaf aphids. Red lesions often form at the feeding sites and heavy infestation can kill the plants. All three species transmit maize dwarf mosaic virus to corn from nearby sources. Johnson grass is one of the common weed hosts for this virus. This may be severe when temperature limits are falling to predict increased population of aphid pests.

Management

Cultural control

Aphids mostly survive on alternative hosts in the absence of host plant. Therefore, the removal of alternative host from the field can minimise pest infestation.

Biological control

There are no established thresholds for aphids on field corn. Only on rare occasions do aphids reach damaging populations. Aphids can be kept below economic levels by the parasite and predators incorporations such as lacewings, lady beetles, and syrphid flies. However, biological control cannot prevent transmission of virus diseases. Biological control and oil and soap sprays are acceptable for use on organically grown crops.

Chemical control

Thiamethoxam 70 WS at the rate of 3g/kg for seed treatment is effective against aphid infestation. Thiamethoxam 25 WG with 24 gram/acre dose gives good results. Reduced temperature and least humidity is crucial in its management decision time as aphids have more population increment at lower temperature regimes. In chemical control for heavy infestation Pymetrozine 50 WG (150 g ha^{-1}) may be used.

4.7. Conclusion

In Pakistan, agrarian side facing certain problems which needs immediate and fixed measures to be addressed (Annonymous 2014). These may include problems of varying intensities. Tentative evaluation, described that total of before and after harvest losses due to pests (weeds, pathogens and insects) is about 45% (25–35% prior to harvest, 10–20% after harvest) on global scale level (Pimentel 1991) Sustainable and precision agricultural success is relied on prototype that attains more profitable cropping, maximum productivity of major cropping intensities and systems, multifariousness of well worthed crops and supplication based production strategies in an integrated approach (Annonymous 2014). Sum of yield damages and losses from full influencing factors to all crops are roughly consideration to be 500 billion U.S dollars in a single year basis (Oerke et al. 1994).

Hence, thought-provoking positive variations towards prosperity that directly has influential effects on subsistence of Pakistani citizens through an Including the specified extremes agricultural operations and processes (Annonymous 2014). Amount of insecticides used on crops causing a huge health perils can be viewed from the facts that the employment of insecticides quantity (% of total utilized on all crops) is from 1% to 47% for wheat to cotton respectively (Palm 1991).

Crop importance is also serving a cause to base production heavily on chemical based control in Pakistan. This may be reviewed from the fact that vital crops, including wheat, sugarcane, rice, cotton and maize have contributions of 25.6 percent of the value added in the whole site of agriculture and 5.4 percent to share of GDP. But, these insecticides are also causing varied levels of resistance problems ranging from bollworms to borer etc. An important factor of wide area resistance issue to insecticides is that least relying on non-chemical controls (or control in an integrated manner).

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Chapter 5

Integrated Management of Insect Pests of Fruits

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Abstract

Fruits are important part of human and animal diet due to their nutritional value. Fruits contribute to major strength of agricultural exports in Pakistan. Insect pests are very important limiting factor in fruit production. Fruits are vulnerable to several types of pests ranging from leaf damage to severe damage even killing of plants. These pests also cause yield losses in the form of crop's market value. The fruit crops pests include insects, mites, pathogens, nematodes, weeds and vertebrates. The insect pests are responsible for severe damage to fruits in the form of direct (feeding on fruits and foliage) and indirect damage (as vectors to transfer disease causing pathogens into the plants). Ecological and economic factors provide the basis for effective pest management of insect pests. The complete knowledge of insect pest, its biology and mode of damage are the factors which help in devising control strategies. Integrated pest management (IPM) is referred as a modern approach for managing pests. Generally, pest elimination is not a goal of IPM; rather it involves compiling detailed and timely information about a crop. IPM seeks to use all appropriate tools and tactics to ensure that pest management decisions are economically, environmentally, and socially sound. This chapter discusses on different fruits along with their ecology, distribution, nutritional value, insect pests and their suitable integrated pest management approaches.

Keywords: Management, Quality**,** Quarantine, Ecology, Biology, Management strategies, Nutritional value**,** Economic and national fruits,

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5.1. Introduction

Fruits are important component of a healthy diet and their adequate consumption could help to reduce a wide range of diseases. They play a significant role in human nutrition, especially as sources of vitamins C (ascorbic acid), thiamine (B1), niacin (B3), pyridoxine (B6), folacin also known as folic acid or folate (B9), vitamin E, minerals and dietary fiber (Quebedeaux and Eisa 1990; Craig and Beck 1999; Micha et al. 2017). According to Food and Agriculture Organization/World Health Organization, botanically, fruit is a part of flowering plant derived from specific tissues of a flower. Fruits contain developed seed for further reproduction. Fruits are important part of human and animal's food. In conventional language, fruit is a fleshy and seed associated structure of plant which is sweet and sour in taste and edible part of plant. Dry fruits and nuts are rich in essential amino acid, vitamins, minerals, dietary fibers and consumed by all age of the people. These are also used as medicines which provide energy and strength to long-term patients seeking out to recover (Emilio 2010). Overall, world loss of fruits due to pests is nearly 40%, in which insect pests share is 15% (Pimentel 1997).

Mango is a fleshy stone fruit which belongs to the genus *Mangifera* and Family *Anacardiaceae* (Morton 1987). It is a native fruit of South Asia from where it is distributed to all over the world. Now it is cultivated almost all over the tropical regions of the world. Mango is the national fruit of Pakistan, India and Philippines besides national tree of Bangladesh. Nutritionally 100 g of mango gives about 250 KJ (60 Kcal) energy. It contains 15 g carbohydrate, 13.7 g sugar, 0.82 g protein, 36.4 mg Vitamin C and 0.38 g fats. South Asia, Central America, Hawaii, South West and Central Africa, Australia, China, Pakistan, India and Bangladesh are main mango growing regions (Anonymous 2014**).** Mango is an evergreen, fast-growing, and long-lived orchard-tree. It is very vigorous with a large canopy and an almost circular projection. The leaves are perennial, deep green, pointed, and shiny, while the inflorescence occurs in panicles consisting of about 3000 whitish-red or yellowish–green flowers. In tropical regions the trees can reach up to 30–40 m in height, while in subtropical areas the growth rate is consistently reduced. The mango fruit has hundreds of varieties, each having its own characteristic taste, shape, and size. Each fruit is 5–15 cm long and 4–10 cm in diameter. Usually its weight ranges from 150 g to around 750 g, reaching approximately 390 g in Sicilian mango fruit (Farina et al. 2013)

Apple, a Pome fruit, belongs to the genus Malus and family Rosaceae and is widely cultivated tree. It is mainly cultivated for its *Malus* species which is consumed by human as fruit. Apple originated in Central Asia, where wild species named *Malus sieversii* L. is still under cultivation. Nutritionally, apple consists of 13.81 g carbohydrates, 0.17 g fats, 0.26 g protein, 85.56 g water and 4.6 mg vitamin-C. The main apple growing areas with the most suitable climate in the world are USA, China, Italy, Turkey, Poland, India, France, Brazil, Pakistan, Iran and Chile (Robinson et al. 2001).

Citrus belongs to the Rutaceae family and includes lime, citron, mandarin orange, bitter orange, persian lime, lemon, rangpur, grapefruit, sweet orange, kinnow and tangerine. The family Rutaceae is supposed to be originated from Southeast Asia, Northeast India, Myanmar and Chinese province Yunnan. Naturally occurring and hybrid cultivars of citrus are orange, grapefruit, lime, lemon and some tangerines (Liu et al. 2012). Brazil, China, USA, Mexico. India, Spain, Iran, Italy, Nigeria, Turkey and Pakistan are main citrus growing countries in the world. As far as nutritional value is concerned, 131g of citrus contain 62 kcal energy, 3.1 g fiber, 70 mg ascorbic acid, 40 mg foliate and 273 mg Potassium.

Grapes are fruiting berries of a deciduous woody vine. Botanically, it is known as *Vitaminis vinifera* L. It belongs to family *Vitaminaceae* and genus Vitaminis. It is consumed raw as a fruit and also used for making its juice, jellies, jams, etc. The main and important product produced by grapes is wine. These are non-climatic type of fruit generally occurring in branches. France is the largest producer of grapes in the world along with well established wine industry. The main growing areas of grapes are China, Italy, USA, Spain, France, Turkey, Chile, Argentina, India and Iran. Grapes are very nutriticious fruit because 100 g grapes contain 28.8 KJ energy, 18.1 g carbohydrates, 15.48 g sugar, 0.1 g fats and 0.72 g protein. More else vitamin B_6 and vitamin K is present in a quantity of 0.086 mg and 14.6 µg, respectively (Ng and Popkin 2012).

Strawberry (*Fragaria ananasa* D.) is a hybrid species which is cultivated worldwide. It belongs to family *Rosaceae* and genus *Fragaria.* Botanically, it is not considered as a berry. This fruit is characteristically famous for its aroma, bright red color, juicy texture and sweetness. Spain, Turkey, USA, South Korea, Egypt, Japan, Poland, Russia, Maxico, Italy, Morocco and Germany are leading producers of strawberry. A hundred gram of strawberry produces 136 KJ energy, 7.63 g carbohydrates, 4.89 g sugar, 0.3 g fat, 0.386 mg manganese and 58.8 g vitamin C (Ng and Popkin 2012).

Banana, botanically called as *Musa sapientum* L., belongs to family Musaceae. Species of this genus is large flowering herbaceous plant. Banana varies in color, firmness and size. Usually, it is curved and elongated having soft flesh with high starch contents. Its rind may be green, yellow, purple, red and brown at ripping stage. In some countries, cooking of banana is also a trend where it is called as plantains. It is native species of South and Southeast Asia. It is grown in almost 107 countries. India is biggest grower of banana followed by Uganda, China, Philippines, Ecuador, Brazil, Indonesia, Colombia and Tanzania (Nelson et al. 2006). One hundred gram of banana contains 371 KJ energy, 22.84 g carbohydrates, 12.22 g sugar, 0.33 g fats, 1.09 g protein, 0.27 mg magnesium and 0.4 mg vitamin B_6 (Ng and Popkin 2012).

Guava (*Psidium guajav*) belongs to family Myrtacae and genus Psidium. Botanical name of guava is *Psidium guajava* L. About 100 species of shrubs and small sized trees are being cultivated in tropics (Julian, 1998). These are innate fruits of Maxico, North America and Central America. Now it is cultivated and naturalized all over in tropic and subtropic regions, Hawaii, New Zealand, Australia, Spain and the Caribbean are main growing areas of guava (Hossen 2015). It is winter fruit of Pakistan. One hundred gram of guava contains about 14.32 g carbohydrates, 8.92 g sugar, 0.95 g fat, 2.55 g protein, 228.3 mg vitamin C and 49 µg vitamin B_9 (Ng and Popkin 2012).

Watermelon, melon, falsa, cheeku, jaman, peach, apricot, leechi, pear, plum and pomegranate are other fruits grown in Pakistan. There is a need to build up a sound and practicable mechanism to protect fruit from pre and post-harvest losses to improve their export and raise the economy of Pakistan.

5.2. Scope of fruits industry with special reference to Pakistan

Cultivation of fruits is an important sub-sector in the agricultural sector of Pakistan. Fruits are valued as protective food. Pakistan has a wide range of agro-climatic condition which allows the production of a variety of tropical and sub-tropical fruits. Major fruit production problems related to planting material, production practices disease and pest control are commonly faced by the fruit producers. The arrangement for the production and distribution of new high yielding plants is extremely poor in the country (Khushk et al. 2006).

Eighty-six percent of our farming community owns less than 5 hectares of land, but has surplus labor force. Demand for fruits in Pakistan has been increasing due to changes in consumption pattern and population growth. A large variety of tropical, sub-tropical and temperate fruits are cultivated in the country. The low level of growth in fruits during 1990s indicates that incentives for the farmers to increase production remained depressed. The cheap availability of the raw material indicates great scope for promoting the export of fresh and processed fruits. On the export side, the regions like Far East, Middle East and Central Asian States of Former Russia are the major markets of Pakistani fruits while a great scope lies as well in exporting to more developed countries like Japan, Canada and Europe (Aujla et al. 2007).

Export of fruits from Pakistan increased from 687 tons of worth US$239 million in 2009-10 to 660 tons of worth US$292 million in 2010-11, thus showing an increase of 22% in terms of value. Agriculture has remained the mainstay of the Pakistan economy as it provides employment to 45% population and input for agro based industry. Agriculture income has created demand for industrial products. Agriculture provides the main impetus to economic growth by creating additional demand of goods and services as a result of higher prices of agricultural produce. Pakistan with its diverse climatic regions holds enormous advantage for production of fruits, vegetables and floricultural (flower farming) products and has a potential to exploit world's US$561 million annual fresh fruits and vegetables market. Pakistan is the sixth largest producer of Kinnow (mandarin) and oranges in the world. Fruits are being grown in all four provinces of Pakistan. The various varieties of fruits are grown over an area of about 758 thousand hectors. The annual production of fruits in Pakistan is estimated at around 6.11 million tons, of which only 660 tons were exported in 2010-11; whereas the rest of them were either consumed locally or perished. Pakistan is exporting fruits to Afghanistan, India, Russian Federation, UAE, Germany and UK. The well-exported fruits are mango, kinnow, apple, dates and oranges.

5.3. Classification of fruits crops

As the ovary develops into a fruit, its wall often thickens and becomes differentiated into three, more or less distinct, layers. The three layers together form the pericarp, which surrounds the developing seed or seeds. The three fruit layers are:

- **Exocarp**, the outermost layer often consisting of only the epidermis
- **Mesocarp**, or middle layer, which varies in thickness
- **Endocarp**, which shows considerable variation from one species to another

Classifying fruits

All fruits may be classified into three major groups on the basis of the number of ovaries and the number of flowers involved in their formation. The following outline includes most of the common types of fruits. A simple key for classifying fruits is provided here. Use these descriptions and the "Key to Fruit Types" provided to identify the types of fruits you observe today.

A. Simple fruits

Simple fruits develop from a single matured ovary in a single flower.

1. **Fleshy fruits**, pericarp fleshy at maturity.

a. **Berry,** consisting of one or more carpels with one or more seeds, the ovary wall fleshy.

(i) **Pepo** (an accessory fruit), a berry with a hard rind, the receptacle partially or completely enclosing the ovary.

(ii) **Hesperidium,** a specialized berry with a leathery rind.

b. **Drupe,** a stone fruit, derived from a single carpel and containing (usually) one seed. Exocarp a thin skin.

c. **Pome** (an accessory fruit), derived from several carpels, receptacle and outer portion. Of pericarp fleshy, inner portion of pericarp papery or cartilaginous, forming a core.

d. **Hip** (an accessory fruit), several separate carpels enclosed within the fleshy or semi-fleshy receptacle.

2. **Dry fruits**, pericarp dry at maturity.

a. **Dehiscent fruits,** those which dehisce or split open when fully mature.

(i) **Follicle,** composed of one carpel and splitting along a single suture.

(ii) **Legume,** composed of a single carpel and splitting along two sutures.

(iii) **Capsule,** composed of several carpels and opening at maturity in one of four ways:

- Along the line of carpel union (septicidal dehiscence).
- Along the middle of each carpel (loculicidal dehiscence).
- By pores at the top of each carpel (poricidal dehiscence).
- Along a circular, horizontal line (circumscissle dehiscence).

(iv) **Silique,** composed of two carpels which separate at maturity, leaving a persistent partition between them.

b. **Indehiscent fruits,** those which do not split open at maturity

(i) **Achene or akene,** a one-seeded fruit with the seed attached to the fruit at one point only

(ii) **Caryopsis or grain,** a one-seeded fruit in which the seed is firmly attached to the fruit at all possible points

(iii) **Samara,** a one- or two-seeded fruit with the pericarp bearing a wing like outgrowth. A modified achene

(iv) **Schizocarp,** consisting of two carpels which at maturity separate along the midline into two one-seeded halves, each of which is indehiscent

(v) **Loment,** having several seeds, breaking into one-seeded segments at maturity

(vi) **Nut**, a hard, one-seeded fruit, generally formed from a compound ovary, with the pericarp hard throughout

B. Aggregate fruits

Aggregate fruits consist of a number of matured ovaries formed in a single flower and arranged over the surface of a single receptacle. Individual ovaries are called fruitlets.

C. Multiple fruits

Multiple fruits consist of the matured ovaries of several to many flowers more or less united into a mass. Multiple fruits are almost invariably accessory fruits.

D. Accessory fruits

Fruits that develop from tissues surrounding the ovary are called accessory fruits. Accessory fruits generally develop from flowers that have inferior ovaries, and the receptacle or hypanthium becomes a part of the fruit. Accessory fruits can be simple, aggregate or multiple fruits.

5.4. Mango

Pakistani mango has fame all over the world for its taste, color, and aroma. Mango export in European countries gives a lot of incentives. Pakistani mango charged about 4-5 $ per Kg in USA. In Pakistan about 46 species of mangoes are cultivated. The main cultivated species have been presented in Table 1.

Mango is grown on large area of Pakistan which is about 0.157 million hectare. Out of which 67% of the area fall in Punjab, 32% in Sindh, 0.8% in Balochistan and only 0.2% in KPK. Pakistan totally produced 17 Million tons mango as mentioned in the Economic Survey of Pakistan 2011-12 (GOP 2011).

The main growing areas of Pakistan for mango are Khanewal, Hyderabad, Multan, Bahawalpur, Rahim Yar Khan, Dera Ismail Khan, Sukkur and Mirpur Khas. Pakistan exports mango all over the world. In 2004-05 there were about 67 countries including major markets of Middle East, Saudi Arabia, USA, Dubai, UAE and Oman. Important buyers of mango in Europe are France, UK and Germany (Akhtar et al. 2009).

Tropical and subtropical climates are most favorable climate conditions for mango. Tree survives at 10-65 ºC but optimum temperature is 21-27 ºC. Highest production and good quality mango is obtained when non-freezing and cool period doesn’t prevail. Drought during fruit setting may increase yield and fruit size. Mango can be grown on wide range of elevation from sea level to 1200 m. Soil requirements are not so important in case of mango. Mango has medium tolerance to water logging soils (Morton 1987).

Bioactive components contained in the different parts of mango have also shown anticancer activity in different tumour cell lines. Mangiferin is a plant natural polyphenol of xanthone structure with C-glucosyl linkage and four aromatic hydroxyl groups that have been considered crucial for its antiradical and antioxidant effect as well as for its pharmacological activity. This polyphenolic xanthonoid is one of the most potent antioxidants known and mainly found in many Anacardiaceae and Gentianaceae plant families (Andreu et al. 2005; Matkowski et al. 2013; Nguyen et al. 2016).

More than 300 insect pests have been recorded as pests of mango crop in different regions of world. A crop loss of 50% or more has been recorded on heavily infested trees (Patel et al. 2004).

Insect pests of mango

5.4.1. Mango plant hopper

Technical name: *Idioscopus nitidulus* (Walker)

Family: Cicadellidae

Order: Homoptera

Fig. 5.1 Mango plant hopper, *Idioscopus nitidulus* W. (Photo credit: Dr. M.A. Khan, UAF)

Biology

Mango plant hopper breeds on the new fleshy leaves and flowers, whereas the similar *I. clypealis* L. breeds on flowers (Hiremath and Thontadarya 1991). Adults (Fig. 5.1) are found throughout the year, and the population increases with the flowering of mango trees. Eggs are laid singly in the florets (100-200 eggs), near venial region of leaves and leaf lamina. The number of generations in a year depends upon geographical regions, flowering and production of new leaves. *I. nitidulus* has one generation per year in northern India but three generations per year in southern India (Viraktamath 1989). It has also been reported that environmental factors such as temperature, humidity and rainfall are important in regulating the population of mango plant hoppers (Tandon et al. 1983).

Description of stages

Adult: Pale yellow in colour and elongated.

Egg: Laid singly in the unopened flowers, tissue of the panicles or young leaves.

Nymph: Pale yellowish in colour.

Damage

Nymphs and adults of *I. nitidulus* suck phloem sap from the inflorescences and leaves. Their feeding and egg laying in any part of plant cause physical injury and hinder the fruit development. Honeydew excretion causes damage due to sooty mold which affects the photosynthetic activity and reduces yield.

Losses estimated due to leaf hopper are about 50% in commercial orchards. Symptoms of attack of plant hopper are marginal chlorosis (yellowing) and necrosis (browning) which is known as “hopper burn” or “tip burn”. Injured leaves fall prematurely.

Management

Physical control

Plants exhibiting the scorch like symptoms or distorted and stunt growth of aster yellow should be removed.

Cultural control

Avoid over fertilization which may increase population of plant hopper. Use of resistant varieties of mango to avoid pest attack.

Biological control

Biological control can be obtained by using *Anagrus atomus* L. an active parasitoid of plant hopper. This is very small egg parasitoid. It parasitizes eggs and turns them into red as wasp reaches end to its incubation. Big eyed bug, damselfly, assassin bug, lacewing are common predators of leaf hopper.

Chemical control

Spray at recommended doses only where it is needed with Confidor 200 SL (80 ml/100 litre water), Actara 25 WP (24 g/100 litre water), Mospilan 20 SP (125 g/100 litre water), Clypso and Imidacloprid 70 WS (100 g/100 litre water). Dipterex 80 SP (100-160 g/100 litre water) also give effective control of plant hopper (Hiremath and Hugar 1989).

5.4.2. Mango mealy bug

Technical name: *Drosicha mangiferae* (Stebbins)

Family: Pseudococcidae

Order: Hemiptera

Biology

Mealy bug has 4-5 instars, 4 in case of female and 5 in case of male. There is only one generation per year. Eggs hatch out in December and January after diapause in ovicases in soil. First instar bugs move towards leaves and molt three times to become adults. Males are similar to female until to reach to prepupa. Prepupa is little bit active for short time. It forms waxy test and molt in pupal stage. Adult (Fig. 5.2) appears in April, mate and again female descends into the ground. Ovicases are produced and eggs are laid. Female may lay about 250-300 eggs which are pinkish and minute (Banta 2016).

Description of stages

Female Adult: Wingless, have oval and flattened body covered with white powder.

Male: Winged; forewings black and hind wings are modified into halters.

Eggs: Oval shaped eggs appear pink at start then become pale.

Damage

Mealy bug is an economic pest in mango orchard. It is a sucking pest and sucks the sap from plant tissues. Excretion of honeydew results in sooty mold development and affects the photosynthetic antivitamin of plant. Once fruit get infested, these can be entirely covered with the white waxy coating of the mealy bug. Fruit can drop due to infestation or fruit may remain on host in dried and shriveled condition. Attack on flowering stage gives bad quality fruit. It is estimated that there are 50% losses caused by mealy bug in mango orchard (Sathe et al. 2014).

Fig. 5.2 Manog mealy bug, *Drosicha mangiferae* S. (Reproduce with permission by: Pooranji et al. 2012)

Management

Cultural control

Soil racking under tree in the month of May should be excavated to the depth of 15cm which expose eggs to sunlight. Hoeing is recommended three times during June, July and August. Alternative host like weeds and grasses should be removed by ploughing during June and July. Flooding of orchard with water is recommended to kill eggs in October (Karar 2010)

Physical control

Apply sticky bands in the beginning of January on main trunk of the tree. Insect will slip and fall or stick with those bands and will be unable to move further. Nymphs near tree base can be controlled by applying insecticide. Funnel trap can also be used against mealy bug (Nandi and Chakraborty 2015).

Biological control

At present there are about 21 parasitoids and 41 predators known, which are used to control mealy bug. *Gyranusoidae tebygi* N. is a parasitoid. *Cryptolaemus montrouzieri* H. is a well-known predator of mealy bug. In Pakistan commercially reared biological control agent is *Aenasius bambawalei* H. which is an important parasitoid.

Chemical control

Chlorpyriphos 500 EC (400 ml/100 litre water), Monocrotophos 36% SL (400-500 ml/100 litre water), Methyl parathion (300 ml/100 litre water), Curacron 250 EC (800 ml/100 litre water) and Lorsban 40 EC (1000 ml/100 litre water) are important insecticides against mango mealy bug (Gulzar 2015).

5.4.3. Mango fruit fly

Technical name: *Bactrocera dorsalis* (Hendel)

Family: Tephritidae

Order: Diptera

Fig. 5.3 Mango fruit fly, *Bactrocera dorsalis* H. (Photo credit: M.A. Khan, UAF)

Biology

Adult female lays eggs under the skin of mango fruits. Females lay about 25 eggs in a day. Eggs are of creamy white and spindle shaped. Female flies puncture the fruit with their ovipositor and also push bacteria inside fruit which cause decay of fruit. After two days, creamy color maggots hatched out from the eggs. It feeds on flesh of fruit. Larval periods ranges from 10-12 days and larvae have 3 instars. The infested fruit drops and larvae go into soil to a short distance. After 11 days, adult emerges from the pupa. Adult fruit flies (Fig 5.3) are predominantly black and have size of housefly (Aluja and Liedo 2013).

Description of stages

Adult: It is little bigger than housefly and stout having brownish colour and transparent wings.

Eggs: Under favorable conditions female lay up to 150-200 eggs.

Maggots: Opaque, legless maggots and yellow in colour.

Damage

Fruit flies have about 61 species. Main sign of infestation is puncture fruits. Fruit fly maggots decay fruit flesh. Flesh is converted into soft, mushy mess. After all these, fruits fell down. Signs of infestation are rot and chlorotic spots. It causes rotting of fruit which makes it unsustainable for the consumption of human being (Simberloff 2009).

Management

Cultural control

Crop sanitation is very important, simple and effective. It consists of cleaning of fallen fruits from orchard which provide breeding place to fruit fly. The collected fruit may burn or feed to animals or pick in plastic bag tightly and put under sun for several days (Liquido 1993)

Physical control

Different types of traps are used to control fruit fly physically. These are of two types.

1) Pheromone traps
2) Bait traps

Pheromone trap (Methyl euogenol), synthetic mimic of sex pheromones of fruit fly, is used to attract male flies in trap. Food bait is used to attract both male and female fruit flies in the trap. Food bait includes the sugar, petroleum jelly, protein hydrolysate and insecticides (Khan et al. 2005).

Biological control

Many biological control agents are found to control fruit fly but level of parasitism is very low as *Diachasmimorpha longicaudata* A. parasitize only 5% fruit flies. *Forpius arisanus* S. also a parasitoid of fruit fly but has very low efficiency of parasitism (Baranowski 1987).

Chemical control

Fruit fly can be controlled by following insecticides which are commonly available in market (Ashfaq 2013).

1) Malathion (1000 ml/100 litre water)
2) GF-120 (1500 ml/100 litre water)
3) Diptrex (100 g/100 litre water)
4) Dimethoate (400 g/100 litre water)

5.4.4. Mango Stem Borer

Technical name: *Bactrocera rufomaculata* (De Geer)

Family: Cermbycidae

Order: Coleoptera

Biology

It is a serious pest of edible fig, mango, guava and walnut. Females cut the tree bark and lays eggs in the cut singly; 200 eggs totally. Eggs are brownish white of about 6.2 mm size. After hatching larvae start tunneling in sapwood and branches of host tree; larvae develop in about 2 years. Pupation occurs in the host tree stem. Adult emerge in July and August. One generation per year is reported. Maximum life of the adult (Fig 5.4) is 8 months (Kfir et al. 2002).

Fig. 5.4 Mango stem borer, *Bactrocera rufomaculata* (De Geer) (Photo credit: M.A. Khan, UAF)

Description of stages

Adult: Adult is dark and two kidney shaped orange yellow spots are present on pronotum

Grub: Grubs have cream colour with dark brown head.

Damage

Female bore into trunk and lay eggs. The larvae emerged from eggs feed on sapwood. They make tunnel measuring 2-3cm in width that cause large damage. Large tunnels damage by interfering with sap flow and affect foliage and fruit production. It often leads to death of tree. Important symptoms of the infestation are the holes on the bark due to feeding (Kumar et al. 2012).

Management

Control measures for *B. rufomaculata* D. are very expensive and laborious.

Physical control

Physical control of mango stem borer is to eradicate its grubs outside the plant. A hard wire is inserted to the borer hole to kill the larvae and pupae. The borer hole is plugged with the cotton soaked in kerosene, petroleum oil.

Cultural control

Pruning and cutting of infested branches and dead tree chipping from the orchards, chipped and burning the infested material, make cultural control.

Chemical control

There are many chemical controls which are used against long horned beetle. Pouring kerosene oil, creosote, petrol, crude oil or formalin into the hole and then closing of entrance with mud or cotton plug soaked with above mentioned compounds can kill the grub. Imidacloprid 70 WS (100 g/100 litre water) is mainly recommended against the pest.

5.5. Apple

A famous saying for apples "An apple a day keeps the doctor away". Apple is considered as a healthy, nutritious and delicious fruit. Pakistan is ranked 6th among the apple producing countries of the world. Color of the fruit is very fantasizing green, yellow and blood red. Potential exists to export fruits and vegetables in surrounding markets of Pakistan like Bahrain, Bangladesh, Dubai, Kuwait, Saudi Arabia, Singapore and Hong Kong. Table 2 present varieties cultivated in different areas of Pakistan (Asif 2002).

In Pakistan, apple is grown as a commercial fruit plant from long time in Dir, Mansehra, Swata, Parachinar, Hunza, South and North Waziristan agencies. Swat region covers an area of more or less 4,000 Sq. miles in the Malakand Division. This area river valley encircled by mountain. Swat district of KPK is the next most Vitaminal area for apple producing states in the districts of Dir, Mansehra, Abbottabad, Hunza and Chitral (Asif 2002). The share of KPK and Balochistan is 60% and 25% respectively in apple production followed by 15% share of Punjab and Sindh in Pakistan (GOP 2012).

Apple is a temperate fruit crop, except in India where it is not grown in those areas which fall in temperate zone. It is grown in Himalayan ranges and at higher altitude. It requires summer temperature near about 21-24^{o}C. Apple grows well in those areas where these trees experience uninterrupted rest in winter and abundant sunshine for good color development. It can be grown at an altitude of 1500-2700m above the sea level and receive rainfall of 1000-1250mm throughout the growing areas. Apple show good performance in well drained, loam soils having depth of 45cm, with pH ranging from 5.5-6.5. Soil should be free from hard substrata and water logging condition (Naor et al. 2003).

5.6. Insect pests of apple

There are many well know insects which are considered as pest of apple fruit and tree.

5.6.1. Codling Moth

Technical name: *Cydia pomonella* (Linnaeus)

Family: Tortricidae

Order: Lepidoptera

Fig. 5.5 Codling moth, *Cydia pomonella* L. (Permission granted by: Jack De Angelis)

Biology

The wingspan of Codling moth is 0.5 to 0.75 inches. Dark brown strip is present at the tip of forewing; codling moth in apple orchards which is distinct from the other butterflies (Fig 5.5). Eggs are laid singly by female on fruits and on leaves late in the season. When eggs are laid firstly they are smaller in size, white needles and plates shaped and milky colored. Before hatch out black larvae become visible inside the eggs. When larvae hatch out its color is white and bears a black head. Mature larvae have 0.5 to 0.75 inches length and are pinkish white with brown heads. Per year 2 to 4 generations of codling moths are recorded (Giner et al. 2009).

Description of stages

Adult: Greyish brown. Fore wings are dark greyish having wavy lines and hind wings are pale grey.

Eggs: Small shining scale like eggs are present singly on the leaves, young fruits or branches.

Larva: Pink or creamy white bearing 8 pairs of legs brown head.

Pupa: Yellowish brown in colour.

Damage

Two types of fruit damages are reported from attack of codling moth; first by entering in the fruit and second by stinging. The larvae pierce the skin of the fruit, bore into the core, damage the seeds and feed in the hole. Immature can enter through either side of the fruit from stem side or from calyx. Faeces can be collected from fruit holes on the surface. This is a visual sign of codling moth infestation (Giner et al. 2009).

Management

Codling moth can be controlled by adopting following control measures.

Cultural control

Proper sanitation conditions should be maintained by removing host trees in the vicinity which are unwanted (apple, walnut and pear) for elimination of pest. This can also be controlled by improving spray coverage. Another method of control is removal of fruit piles and picking boxes. Manual removing of dropped fruits during each generation time may help to reduce population.

Physical control

Pheromones (Pherocon-r 1CP) can be applied for monitoring of the pest. Sprayable pheromones are recommended for its control commonly available but they have very short residual period. Sex pheromones can be applied in different types of traps.

Biological control

Although natural enemies of codling moth are still unknown to keep the pest population below economic threshold but releasing of *Trichogramma platneri* N. the egg parasite, can be applied to reduce codling moth population, Researches revealed less effectiveness and cost expensiveness of this technique for the growers.

Chemical control

Chemical insecticides can cause mating disruption and directly kill the insects. The insecticides used for the control of codling moth are Isomate-C Plus, Isomate-C TT, CheckMate CM and Suterra Puffer. Insecticides used against codling moths are Chlorantraniliprole 18.5% SC (50 ml/100 litre water), Spinetoram (700 ml/100 litre water), Acetamiprid 20 SP (40-50 g/100 litre water), Lambda-Chyalothrin 2.5 EC (250 ml/100 litre water) and Thiacloprid 48 SC (40 mg/100 litre water).

5.6.2. Apple maggot

Technical name: *Rhagoletis pomonella* (Walsh)

Family: Tephritidae

Order: Diptera

Biology

Apple maggot is innate pest of the eastern U.S. and Canada. It was discovered in 1979 in Origin and then moved into states of California, Washington and other Western parts of U.S. Adult flies are smaller in size as compared to houseflies having clear wings with black bands, white spots are present on the back of thorax, and a black abdomen having light-colored cross bands. Four cross bands on female abdomen and three on male. Eggs are inserted into shoots, stems and leaf veins. Nymphs emerge after 10 days which are wingless. They have five developmental stages between 12-30 days. Nymphs gain wings as insect grow larger. This pest has usually one generation per year but some may have six (Filchak et al. 2000).

Description of stages

Adult: Black in colour and smaller than house fly. White bands are also present on its abdomen. Wings are marked with four oblique black bands.

Eggs: white, elongated and slightly curved.

Damage

Female of apple maggot lays single egg under the skin of fruit. The larvae make holes in fruit and starts feeding on flash. This is the main damage which make the fruit unfit for consumption. The insect pest causes injury to the plant and bacterial activity causes rotting of fruit which makes the fruits unfit for consumers.

Management

Physical control

Apple maggot is physically controlled by using different traps which may be pheromone traps or may be baited trap. Baited trap used are bait + GF120 to control adult flies. Mass trapping is done with plastic sticky sphere and dark-colored trap. One to two traps per tree can be used for effective control on pest.

Chemical control

Apple maggot can be managed by using organophosphate based insecticides for emerging adult flies. First application of spray can be done after 7 to 10 days when first fly emerge. After that spraying can be done at 10 to 14 days interval when adults are vigorous and can be trapped. Chemical used against apple maggots are Spinosad (GF-120) 240 SC (30 g/100 litre water) and Phosmet (Imidan) 50 WP (0.3-1.12 kg/100 litre water). For bait purpose use of Corn Gluten Meal + Spinosad (Entrust) is recommended.

5.6.3. Bud moth

Technical Name:	*Spilonota ocellana* (Denis and Schiffermuller)
Family:	Ortricidae
Order:	Lepidoptera

Biology

Larva is dark brown caterpillar having glossy black head. Mature mot hs are of gray color; look like to codling moth but are smaller in size with white strip transversely on the middle part. There are two generations per year. Adults resume activity in May and lay eggs which hatched out in last dates of June to July. In summer larvae feeds on leaves and entire surface of fruit. The adults start to appear in September and October. It is believed that adult emerged in summer can overwinter. These larvae appear in the end of winter, pupation occur in spring, adults emergence take place in May.

Description of stages

Adult: Adult of Apple bud moths is $^1/_2$-inch (12.5 mm) long. They are triangular moths with a mottled gray-brown color pattern with prominent mouthparts that prolong beyond the head.

Eggs: Eggs are green and near hatching is bronze. Eggs laid on upper leave surface in the masses having almost 150 eggs.

Larvae: Moth larvae have light brown to greyish in colour. And about ¾ inch (19mm) long.

Pupae: The colour of the Pupae is light brown and their length is $^{1}/_{25}$ inch (10mm) long.

Damage

First the newly emerged buds and leaves in spring are attacked by this pest but it is not a problem unless populations are very high. The young trees or nursery stock can be seriously damages by boring of larvae into growing shoots and resulting restricted growth or abnormal tree form. Larval feeding on fruit by mature larvae can cause damage similar to leaf-roller feeding in early season. The young larvae feeding can cause cluster of tiny, circular excavations in the fruit in mid- to late summer.

Management

Physical control

In recent years, this pest becomes the threat for organic apple orchards and the best time to suppress this pest is before bloom. The monitoring orchard in July and August is also helpful to manage the pest. The pheromone traps can be installed in the plantation by 1st May but their maintenance should be carried out throughout the growing season.

Chemical control

Synthetic pesticides are applied in conventional orchards for easy control of bud moth. Spinosad (Entrust) 240 SC (30 g/100 litre water) can be used for control during pre-bloom season and 2 spray in June and July. Alternation of spray with *Bacillus thuringiensis* may help to reduce risk of development of resistance. Spray will be effective if applied in warm and dry weather when larvae are immature.

5.6.4. Woolly apple aphid

Technical name:	Eriosoma lanigerum (Hausmann)
Family:	Aphididae
Order:	Homoptera

Biology

The main attacking region of woolly apple aphids is trunk, limbs, shoots and seldom on fruit (Fig 5.6). Wool like white and waxy masses of bark feeding aphid bodies covers the tree completely. Aphid found on tip of the tree in clusters and on roots especially during winter season. Migration of nymphs can be observed in downward and upward on the infested trunk during summer and fall.

Description of stages

Adult: Winged adult female have a pair of transparent wings while wingless adult female have purple brown color and its body is covered with waxy threads.

Eggs: Oval shape eggs

Nymph: Bluish white in color.

Damage

Whitish colonies are mostly found on the plants which are newly grown and have succulent tissues, unhealed pruning wounds, water sprouts or cankers. High incidence of pest causes sooty mold due to honeydew excretion of aphid and galls on different plant regions. Settlements which are beneath the ground can be found all over the year in the root systems. Severe attack on roots can arrest or kill the growth of young trees, but damage to mature once is less. Woolly Apple Aphid can also transmit *Pezicula malicorticis J.* which is also known as apple canker.

Fig. 5.6 Woolly apple aphid, *Eriosoma lanigerum* H. (Reproduced with permission by: Charley Eiseman, 2011)

Management

Cultural control

Most recommended and mostly used cultural control practice is the use of resistance rootstock. Winter Banana (an apple variety) is known as most susceptible variety to aerial galls. Yellow Newtown is mostly found under attack on the calyx end. Rootstock Rubasta-5 and number-111 and -106 are resistant to attack of this pest.

Biological control

Aphid parasite *Aphelinus mali H.* can control the colonies of aphid on aerial portion of the tree.

5.7. Citrus

Citrus is the 2nd largest fruit exported from Pakistan. It is important due to its nutritious value as well as due to its economic importance. Citrus is not a single fruit it is a combine term used for Citrus fruits including mandarins, grapefruit, oranges and lemons, from all these mandarins (Kinnow) is of great importance to Pakistan. The soil and climate plays an important role in giving a unique taste and flavor which is distinguished from all cultivars grown all over the world. Main citrus growing areas of Pakistan are Distract Sargodha, Sahiwal, Jhang, Lahore, Gujranwala, Sialkot, Minwali and Multan, in Punjab province. Similarly, Mardan, Peshawer, Swat, Swabi, Noshera and Hazzara in KPK, Sukkur, Khairpur and Nawabshah in Sindh and Mekran, Sibi and Kech in Baluchistan are main areas of citrus production (Ahmad et al. 2005). Main citrus growing varieties of Pakistan are given in table 3.

Pakistan is growing citrus on about 0.19 million hectare area on an average. The annual production increases from 1,760 (000) tons in 2003-04 to 1,832 (000) tons in 2011-12. As far production of citrus on province level is concerned, Punjab contributs 95.6% share in production on 94.5% of total citrus growing area while Sindh shares 1.6%, KPK 2.1% and Baluchistan contributes about 0.7% in total production (GOP 2012).

Citrus grows well in the tropics. Sweet oranges proliferate in this region, but their skins remain pale greenish and do not develop a bright orange color due to a lack of lower temperatures before harvest. In subtropical climates with hot, humid summers and mild winters, large, sweet fruits with high juice quality and content are produced. In semitropical and Mediterranean climates citrus fruits have the brightest skin color, smoothest skins and an optimal blend of sweetness and acidity for fresh fruit production. Citrus crops can be grown on the soil varying from sands to clay loams with different water holding capacities, drainage conditions and irrigation needs. Root growth occurs when soil temperatures range from 25 to 30 °C with most active root growth occurs between 53.6 to 95 °F soil temperatures. Well-drained soils with a pH of 5.5 to 7.0 and low salinity are ideal for the production of citrus. Yields are almost halved when pH drops to 4.5 (Radoglou et al. 2008).

5.8. Major pests of citrus

Citrus production is mainly effected by pests. They reduce production as well as damage the export quality of the fruit. Major pests from which we are dealing now are:

5.8.1. Citrus leaf miner

Technical name: *Phyllocnistis citrella* (Stainton)

Family: Gracillariidae

Order: Lepidoptera

Biology

Adult citrus leaf miner is a small moth about 2 nm long (less than 0.12 inches) having wingspan of about 4 mm (about 0.25 inches). Wings are silver and white with brown and white glittering markings and distinct dark spots on each wing tip. After the eggs are laid off, they hatch within 4-5 days; newly hatched larvae in the leaf begin shallow, meandering coal feeding immediately. With the increase in size of the larvae when the mines become more apparent, larvae molt 4 times in 1-3 weeks. Mature larvae pupate inside the mine. It rolls edges of leaves and cover the pupa with silk for protection. Whole life cycle of leaf miner is completed in 2-7 weeks, depending upon different weather conditions (Badawy 1967).

Description of stages

Adult: Silvery white colour. Fringes of hairs are present on fore and hind wings. Fore wings also have black spots along the tip.

Eggs: It lays eggs on the lower surface of the leaves which are minute and transparent. 2 or 3 eggs are present per leaf and hatch in 2-10 days.

Larva: Its colour is pale green or pale yellow. Larva has no legs and has well developed mandibles.

Damage

Citrus leaf miner larvae make tunnels and feed inside these hollow tunnels, known as mines in the leaves. This is the most common pest on citrus as well as found on closely related plants (calamondin and kumquat). Mining is always done by the larvae on lower side of the leaves or on the surface to make them twist and look slanted. Established citrus plants more than 4 years old generally do not respond to damage like leaves growth and fruit yield. Citrus leaf miner may cause damage to nurseries and the growth of young trees is arrested by leaf miner pests.

Management

Mechanical control

Bait traps with pheromones (insect attractant) can be used for citrus leaf miner to control when moths fly and start depositing eggs. From March to November pheromone traps can be hanged at about chest height. Effective control depends upon frequency of trap per unit area.

Cultural control

Citrus leaf miner attacks the new citrus trees flush. Pruning of branches more than once in the year should be avoided so flushing cycle remains consistent. After hardening of the leaves pest will not be able to mine in the blades. Do not cut the leaves of damaged citrus because the leaves which are undamaged still producing food in trees. Do not apply fertilizer when leaf miner population is high and flushing growth because it can cause serious damage. Resistant varieties of citrus should be encouraged.

Biological control

Citrus leaf miner has many parasites including *Cirrospilus* and *Pnigalio* species but they are pesticide sensitive. Broad spectrum insecticides may interrupt their field Vitamins. All over the world, citrus leaf miner population is effectively controlled by using parasitic wasps.

Chemical control

Because leaf miner can hinder the growth and development of the young trees, so the insecticide application is necessary for the protection of nursery trees and new planted nurseries of the citrus. Imidacloprid (20-50 ml/100 litre water) can give long term (1 to 3 months) control by application via the irrigation for immature trees or to the soil of potted plants. Thiamethoxam 70 WS (350 g/100 litre water), Chlorantraniliprole 18.5 SC (1200 ml/100 litre water), Methoxyfenozide 5 EC (400 g/100 litre water) and Acetamiprid 20 SP (200 g/100 litre water) also give effective control. Ovicides such as oil or Diflubenzuron (Micromite) should be applied during peak flights of moths.

5.8.2. Asian Citrus Psylla

Technical name: *Diaphorina citri* (Kuwayama)

Family: Psyllidae

Order: Hemiptera

Biology

Length of adult is 3-4 mm long with dotted brown body. Head is brown, but *Trioza erytreae* have blackheads. Citrus psyllid nymphs are 0.02 cm long in length, from 0.15 to 0.17 cm, in 5th instar. These are generally yellow and orange in color. Citrus psyllid eggs are about 0.3mm long, elongated, almond-shaped, thick base and taper toward the distal end. Eggs are laid in the leaf buds between growing tips. Females can lay more than 800 eggs in their lives. Complete life cycle requires 17-45 days, depending upon the environmental conditions. Adults may live for several months. There are 9 to 10 generations in a year. However, 16 generations are observed in field cage (Pluke et al. 2008).

Description of stages

Adult: Brown colour while head is pointed and its colour is lighter brown. Length of adult is 3 mm. Wings are semitransparent and membranous.

Eggs: Pale yellow whose length is 0.3mm

Nymph: The nymphs have orange yellow colour and are louse-like.

Damage

The attack of psyllid causes huge loss of sap from the foliage. It also transmits pathogen *Candidatus liberibacter* that can cause Huanglongbing also known as citrus Greening disease. Symptom of greening is named as citrus chlorosis in Java, leaf mottling in Philippines, likubin in Taiwan, Honglongbing in China and citrus greening in Pakistan (Halbert and Manjunath 2004).

Management

Mechanical control

Mechanically citrus psylla can be managed by the installation of yellow sticky cards for one trap per 1/4 Km. Traps can work more effectively when trees are fully grown and young leaf flushes are absent and especially after a flush has stiffened. This pest is attracted toward newly grown leaves because they have volatile signals in addition to the color in leaves. This method is only effective for monitoring adults.

Biological control

Natural enemies of *Diaphorina citri* K. include syrphids and chrysopids, more or less 12 species of coccinellids, and several parasitic wasps; most important is *Tamarixia radiata* (Waterston). *T. radiate* W. was adopted in citrus growing areas but due to low parasitism rate it was not counted as efficient parasite. Thus, these releases are now confined on residential citrus where area wide pesticide applications are difficult to achieve the control (Grafton-Cardwell et al. 2006).

Chemical control

It is a general principle that only one pesticide can't control all stages of citrus psylla because all stages of the pest are difficult to contact with insecticides. Neonicotinoids have systemic mode of action so these are considered to be the best for application during June and September. Tree injection technique can also be effective technique against citrus greening if tree is injected with tetracycline antibiotics where the vector is kept under control. Fenpropathrin EC (300 g/100 litre water), Beta-Cyfluthrin SC (250 ml/100 litre water) and Zeta-Cypermethrin 10 EC (330 ml/100 litre water) also give effective control to citrus psylla (Grafton-Cardwell et al. 2006).

5.8.3. Citrus fruit fly

Technical name: *Bactocera zonata* (Saunders)

Family: Tephritidae

Order: Diptera

Fig. 5.7 Citrus fruit fly, *Bactocera zonata* S. (Photo credit: Dr. J.N. Ahmad, UAF)

Biology

Adult females lay eggs under the skin of citrus fruits. On an average female lay about 25 eggs in a day. Eggs are of creamy white and spindle shaped. Female fly punctures the fruit with her ovipositor which also pushes bacteria inside fruit which cause decay of fruit. After two days maggots hatched out, this is of creamy color. It feeds on flash of fruit. Larva is of creamy color. It feeds on flash of fruit (Fig. 5.7). Larval period 10-12 days, larvae has 3 instars. The infested fruit drops and larvae go into soil to a short distance. After 11 days adult emerges from the puparium. Adult fruit flies are predominantly black and have size of housefly (Aluja and Liedo 2013).

Description of stages

Adult: Reddish brown and have yellow cross bands on abdomen. Wings are transparent. Small brown spot is present on the tip of each wing

Maggots: Dirty white, wingless and headless.

Eggs: White color with cylindrical shape.

Damage

Fruit flies have habit to lay eggs inside the fleshy part of the fruit and vegetables. The maggots which often feed on soft flesh of the fruit result in conversion of flesh into very soft and mushy mess. The main sign of infestation is presence of punctured fruit in the orchards. Fruit fly plays an important role in decaying of fruit flesh. Signs of infestation are rot and chlorotic spots (Simberloff 2009).

Management

Cultural control

Crop sanitation is very important, simple and effective. It consists on cleaning of fallen fruits from orchard which provide breeding place to fruit fly. The collected fruit may be burnt or fed to animals or picked in plastic bag tightly and put under sun for several days (Liquido 1993).

Physical control

Different types of traps are used to control fruit fly physically. These are of two types.

1) Pheromone traps
2) Bait traps

Pheromone traps are used to attract male insect in trap to stop reproduction for new generation. Methyl euogenol is the synthetic mimic of sex pheromones of fruit fly which attracts male into the trap.

In bait traps beside of using pheromones food bait is used to attract both male and female in the trap, food bait included the sugar, petroleum jelly, protein hydrolysate and insecticides for male methyl euogrnol used and for female sugar (Khan et al. 2005).

Biological control

Many biological control agents have been found to control fruit fly. Several species of wasp attack on maggots e.g., *Diachasmimorpha congicaudata* A. but their level of parasitism not greater than 5%. *Forpius arisanus* S. also a parasitoid of fruit fly but have very less efficiency of parasitism (Baranowski 1987).

Chemical control

Fruit fly can chemically be controlled by following pesticides which are now a days commonly available in market (Ashfaq 2013).

1) Malathion (1000 ml/100 litre water)
2) GF-120 (1500 ml/100 litre water)
3) Diptrex (100 g/litre water)
4) Dimethoate (400 g/litre water)

5.9. Guava

Guava, *Psidium guajava* L., belongs to family Myrtaceae. Guava is a tropical fruit which is rich in nutritional value. Its unique flavor, taste and health-endorsing qualities, easily fit it in the nutritional foods category which is often known as "super-fruits". In contemporary conditions guava is mostly grown in Hawaiian Island, South Asian countries, Cuba, India, Brazil and Pakistan. Almost all the provinces of Pakistan are growing guava. The major growing areas are Gazipur, Shariqpur, Lahore, Sangla Hill, Gujranwala and Sheikhupura. Commercially grown varieties of guava in Pakistan given in table 4.

Total production of guava reported in 2011-12 as 527 (000) tons. Pakistan is on 2nd number in world in the production of guava. Punjab contributes 80% of total guava production and remaining 20% is shared by all three provinces (GOP 2012).

Tropical and sub-tropical regions are suitable for successful guava production. The yield can likely increase and quality enhanced in areas having discrete winter season. Guava can be grown on 1515 m altitude from sea level. Young plants are susceptible to cold and drought. For blossoming and fruit development dry climate is needed but very warm climate at the stage of fruit development can provoke fruit dropping. Performance of guava is well in heavy clay soil to light sandy soil. It can tolerate pH range from 4.5 to 9.4, and is not salt resistant (Anonymous 2011).

5.10. Insect pest of guava

5.10.1. Guava fruit fly

Technical name: *Bactrocera zonata* (Saunders)

Family: Tephritidae

Order: Diptera

Biology

Bactrocera zonata S. is a luminously colored little fly, approximately 5.4 mm in length. Predominately black yellow stripes, it can be distinguished by the color of thorax, and mainly by the black spots on face when united form a black crosswise band. Eggs are deposited by the adult fly into the fruit. Eggs hatch within 22-26 hours at 25 °C. Larvae damage fruit by tunneling. Larvae from a puparium develop into adult fruit fly. Adult flies emerge from puparium. Adult females cause blemishes inside fruits.

Description of stages

Adult: Reddish brown and have yellow cross bands on abdomen. Wings are transparent. Small brown spot is present on the tip of each wing.

Maggots: Dirty white, wingless and headless.

Eggs: White colour with cylindrical shape.

Damage

Adult flies lay eggs in the fleshy portion of the guava fruit which is freshly developed. When maggots emerge from the eggs they start feeding inside the guava fruit. As a result of the feeding, the fleshy fruits become soft and mushy mess. The damage causes guavas to rot. Fruit fly infestations often spread quickly, but prompt treatment can get populations under control.

Management

Guava fruit fly can be controlled by adopting following control measures.

Cultural controls

Ideally, it would be best to avoid planting fruit fly susceptible trees. Management will be easier on multi-grafted fruit trees. More else extra efforts are needed by time, skills and tools for keeping the plant height below 2. 5m. A good thumb rule is "when you can't reach the height of the plant, cut it off". In areas where winter in prolonged fruit fly die by itself which make the control easier. Due to increasing population numbers, late fruiting trees may be severely affected, through successive generations (Khan et al. 2010).

Physical control

To break the cycle of infection all damaged fruits must be destroyed. Remove any fruit from the tree with weeping or dimple clear sap because this is a sign that eggs have already been laid in the fruit. Destroy the fruit by immersing it in water and feeding it to poultry. Mechanical methods of controlling the oriental fruit fly make protective coverings or traps. Shrubs within 91.44m of larval hosts may be used advantageously in placing traps. The use of protective coverings is more effective than the use of traps (Ashfaq 2013).

Biological control

Fruit fly has no specific predator. Braconid wasps which are egg parasites; spiders catch adults in webs; ants and ground beetles feed on maggots; predatory flying insects such as robber flies and dragonflies are important.

Chemical control

Fruit fly can be controlled by following pesticides which are easily available in markets.

1) GF-120 (1500 ml/100 litre water)
2) Malathion (1000 ml /100 litre water)
3) Laser (210 g/litre water)
4) Diptrex (100 g/litre water)
5) Dimethoate (400 g/litre water)

5.10.2. Black scale

Technical Name: *Saissetia oleae* (Olivier)

Family: Coccidae

Order: Hemiptera

Biology

It is difficult to identify scales at first sight. Many people have no idea about them that they are insects. Immature and adult females are wingless and they are immobile. If we try to recognize them on the basis of body parts then there are no body parts. Head is no separate body parts, specific character of adults female are that they have oval or round, flattened to humped appearance. Adult males are the easiest to identify and have a dark brown to black body up to 5.08 mm long and 3.175 mm wide with distinguishing H-shaped ridges on their backs.

Females of many scale species have parthenogenesis. On maturity level, laid eggs are kept hidden under the body cover. Tiny crawlers emerged after hatching of eggs are yellow mostly. The crawlers cab blown by wind to other plants or walk over the plant surface. They establish and start feeding within a two days after emergence (Kapranas and Tena, 2015).

Description of stages

Adult: Dark brown to blackish in color and have convex shape with H-shaped ridge on their back.

Eggs: Pale yellow in the start then turn into orange colour

Nymph: Pale yellow to light brown in colour.

Damage

A severe black scale infestation affects the vigor of guava trees and its productivity. Scales insects have sucking mouthparts which are straw like and they suck fluid through them. Scales insects can occur on fruits, bark and on leaves. Symptoms include yellowing of leaves, wilted look and premature dropping of leaves. Scales infestation results in curled and deformed leaves or twigs. Armored scales infested bark and cause cracking of bark and exude gum. There are certain armored scales which feed on fruit and have aesthetic value (Martinez-Ferrer et al. 2015).

Management

Guava black scale can be controlled by adopting following control measures.

Cultural control

Proper irrigation with appropriate growing condition is helpful. Removal of severely infested plant parts for eliminating scales from individual plant parts is also a promising cultural practice. Opening up tree canopies for eradicating scale insect is also very helpful. Moreover, pruning exposes insects to heat which increases the mortality rate of the insect. Preplanning the trees or plants for landscaping also helps in choosing plants which are pest free and most suitable to the local climate.

Biological control

Some predators and some small parasitic wasps especially bugs, lacewings, beetles and mites are few biocontrol agents of black scale.

Chemical control

Horticultural oils and certain systemic insecticides are recommended where scales are abundant enough and cause severe damage. Acephate (various brands) 40 EC (400 g/100 litre water) and imidacloprid 70 WS (100-250 ml/100 litre water) and certain other systemic insecticides are effective against scale insect. Systemic insecticides provide an edge for control where temperatures limit the use of oil sprays, similar is in the case of soil-applied products, where spraying the plant (large trees) is not practical (Martinez-Ferrer et al. 2015).

5.10.3. Thrips

Technical Name:	*Thrips tabaci* L.
Family:	Thripidae
Order:	Thysanoptera

Biology

The adults are minute and having slender body. Wing of thrips are hairy from the margins on both sides more else the wing are very narrow. Immature on thrips called as larvae or nymphs are similar in appearance as with adults, having narrow abdomen but these are wingless. Female lays eggs in plant tissues. Just a moment before hatching squeezing of egg occurs, it grows up to pre-pupal stage; they stop feeding and crawl down into the soil, and pupate in resting stage. After pupation adult emerge. Development from egg to adult takes 8-20 days but this depends upon temperature (Parker et al. 2013).

Description of Stages

Adult: Blackish or yellowish brown. Females have wings while male are wingless.

Eggs: Kidney shaped eggs are laid by female singly in slits.

Nymph: Pale in colour. They resemble to adults but are smaller and wingless.

Damage

Thrips feed on soft developing tissue. Thrips feeding result in the formation of scratches on leaves and fruits known as stippling results in arrested growth. Damaged leaves may become distorted. Infested leaves get rolled, discolored and dropped prematurely. Petals may exhibit “color break,” which is pale or dark discoloring of petal tissue, it is killed by thrips feeding before buds opened (Parker et al. 2013).

Management

Cultural control

Thrips species that feed on many different plant species often move into gardens and landscapes when plants in weedy areas or grasslands begin to dry in spring or summer. So it is wise to avoid planting susceptible plants next to these areas or to control nearby weeds that are alternate hosts of certain thrips. In small gardens, thrips can be controlled with a spray of water. Prune and destroy injured and infested terminals when managing a few small specimen plants in the landscape. Regular pruning of infested parts can be especially effective with the gall-making Cuban laurel thrips

Biological control

Mites, including minute pirate bugs and predaceous mites, help to control certain plant-feeding thrips species. Certain predators and parasites of thrips are produced commercially and can be purchased through the mail, little or no research has been conducted on the effectiveness of releasing thrips predators or parasites in landscapes and gardens. Following are the some natural enemies of thrips; *Chrysoperla* spp., *Orius* spp. and *Amblyseius*, *Euseius, Neoseiulus* spp.

Chemical control

Effective against thrips infesting guava fruit trees are Mospilas 20 SP (125 g/100 litre water) and Confidor 200 SL (80-100 ml/100 litre water).

5.11. Conclusion and future perspectives

Fruits are important component of a healthy diet and adequate consumption could help to reduce a wide range of diseases. They play a significant role in human nutrition, especially as sources of vitamin C (ascorbic acid), vitamin A. thiamine (B1), niacin (B3), pyridoxine (B6), Folacin (also known as folic acid or folate), (B9), vitamin E, minerals, and dietary fiber. Fruit industry can play an important role to manage the food security issue of the world. The low production of fruit crops is attributed to abiotic and biotic factors especially insect pests. The insect pests are the major constraints in the enhancement of production and protection of fruits. These cause serious damage to fruits by deteriorating the export quality/quantity of fruits. The problem can be solved through adoption of integrated pest-management and ecologically based pest-management systems practices. The presence of pesticide residues in fruit products is another major issue in fruit production. Therefore, the toxic persistent insecticides should not be used for fruit production. The use of integrated pest management approaches will help for sustainable insect pest management as well as to increase the quality and quantity of the fruit crops. The adaptation of recommended pre- and post-harvest management practices can bring a positive change in the export of fruits from Pakistan and uplift the livelihood of the farmers in the country.

Table 1 Main cultivars/varieties of mango in Pakistan

Almas	Alphanso	Anmol
Anwar Retaul	Baganpali	Baramasi
Budhia Muna Syed	Burma Surkhi	Chunsa Kala
Chunsa Late	Chunsa Rampuri	Chunsa Samar Bahisti
Collector	Dosehri	Early Gold
Fajri	Gulabe Khas	Haden
Jagirdar	Keitt	Kingstone
Langra	Malda	Malda Late
Maya	Momi K	Neelum
Pop	Retaul Late	Salehbhi
Sanglakhi	Saroli	Saroli Early
Saroli Late	Sensation	Sindhri
Sobhedi Ting	Springfels	Swarnarika
Taimuriya	Tommy	Atkins
Totapari	Yakata	Zafaran
Zardula		

Table 2 Main varieties of apple in Pakistan

1. Golden Delicious	2. Red Delicious	3. Amri
4. Anna	5. Sky Spur	6. Red chief
7. Spartan	8. Ida Red	9. Starking Delicious
10. Khandhari	11. Red Golden	12. Nagget
13. Golden Russet		

Table 3 Main growing varieties of citrus fruit in Pakistan

Types of Citrus	Varieties
Sweet Orange:	Succri, Mausami, Washington Navel, Jaffa, Red Blood, Ruby Red and Valencia Late.
Mandarins:	Feutrells Early and Kinnow
Grape Fruit:	Mash Seedless, Duncan, Foster and Shamber
Lemon:	Eureka, Lisbon Lemon and rough Lemon
Lime:	Kaghzi Lime and Sweet Lime

Table 4 Commercially grown varieties of guava in Pakistan

Variety	Characteristics
Safeda	It is of medium size, thick white flesh, and very thin skin few seeds.
Karela	Poor bearer, medium large, pear-shaped furrowed, rough skin with soft granular white flesh.
Allahabad	Large white fleshed with few fairly hard seeds
Seedless	Medium to large, with thick white flesh, firm to soft, light bearer.
Red fleshed	This variety is of medium size high in pectin with many fairly soft seeds, and good for jelly.
Apple color	It is slightly oblate deep pink skin, medium size, moderate amount of seeds, very sweet flavor.

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Chapter 6

Integrated Insect Pest Management Strategies for Major Vegetables Crops

Ahmad Nawaz, Muhammad Dildar Gogi, Muhammad Sufyan, Muhammad Jalal Arif and Manuel Plantegenest[†]

Abtract

Hunger and food shortage is a widespread and growing phenomenon of the global world and needs to be managed. Vegetables are an important element in the culture and economy of the world. They are an important constituent of the human diet and their contribution for human health has been increasingly recognized. Vegetables are grown in an agroecosystem of both biotic (biological) and abiotic (physical) factors. These factors affect the vegetable production collectively from sowing till postharvest handling. The second important factor is crop production selection by the farmers without conducting any preliminary marketing and without any signed contracts for produce realization. Therefore, vegetables need to be managed properly during the whole production cycle to overcome the decrease in vegetable production. The aim of this chapter is to highlight the scope of vegetable industry for food security, classification of different vegetables, factors which affect vegetable production including their integrated management with special reference to insect pests, postharvest handling and marketing of vegetables with future perspectives of vegetable production. This will help to understand the current issues of vegetable

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industry and their management to improve the vegetable production for food safety and security.

Keywords: Vegetables, Classification of vegetables, Vegetable pests, Integrated Pest Management, Postharvest management, Food security

6.1. Introduction

Food shortage is a widespread phenomenon of the world and billions of people are suffering from hunger all over the world. The Food Agricultural Organization (FAO) predicted the dramatic increase in food demand due to increase in population which would be eight billion by the year 2030 (FAO 1995). During the last three to four decades, a lot of progress has been made in agriculture towards feeding the global population that has increased over seventy percent, and per capita food consumption that has also increased twenty percent. It is predicted that in the year 2030, the crop output is projected to be seventy percent higher than current output (FAO 1995). The horticultural crops (fruits and vegetables) will play a crucial role in providing essential nutrients (vitamins, minerals, dietary fibre) to the world. In this way, they will help feeding the population in all developed and developing countries of the planet Earth. Vegetables are gaining commercial importance because of their increasing recognition in the human diet (FAO 1995; Salunkhe and Kadam 1998).

Vegetable crop production is a popular hobby and an important element of our culture. It has an immense value for recreation and relaxation. Vegetables are eaten for their unique taste and flavor and also serve as a rich source of vitamins. They provide certain nutritional constituents in which other food materials are deficient. Therefore, consumption of vegetables provides taste, palatability, fibre for digestion as well as prevent from constipation. They are also helpful for neutralizing the acids produced during consumption of pretentious and fatty foodstuff (Terry 2011). Vegetables can be divided into different categories as a source of nutrition, as some vegetables are good source of carbohydrates (sweet potato, potato, onion, garlic, methi and leguminous crops), proteins (garlic, peas, beans, and leafy vegetables), vitamin B (peas, garlic, tomato) and vitamin C (leaves of radish, green chillies, Cole crops and leafy vegetables) (Roy 1993). In addition, some vegetables (leafy vegetables, drumstick pods) also provide essential minerals. Conclusively, the nutritional composition of vegetables depends upon genetic as well as environmental factors (temperature, light, moisture) including nutritional status of the soil in which the vegetable is grown (Roy and Chakraborti 1993). Other factors which are also responsible for the nutritional composition of vegetables are cultural practices, stage of maturity, postharvest handling, and storage conditions. Moreover, many vegetables are processed (cooking and canning) which also influence the nutrient content of vegetables (Salunkhe and Desai 1984; Salunkhe 1991).

Vegetables are grown in an agroecosystem which comprises both biotic and abiotic components and the interaction within and between them. The components are connected to each other in such a way that any change in one component is likely to affect the other. The biotic components include vegetables and other crops in the field: weeds, insects, pathogens and natural enemies of vegetable pests while the abiotic components include soil, water, temperature, light, humidity, wind, fertilizers and agrochemicals. These factors affect the vegetable production collectively. The aim of this chapter is to highlight the scope of vegetable industry, classification of different vegetables, factors which affect vegetable production including their management and postharvest handling and marketing of vegetables with future perspectives of vegetable production.

6.2. Scope of vegetable industry with special reference to Pakistan

Vegetables are defined as the leafy green, stem, and root or even flower stalk portion of an edible plant. They are grown worldwide on good and marginal land, on small and large farms, and by large commercial growers as well as small subsistence farmers. They provide important constituents of diet like vitamins, minerals, dietary fibre and phytochemicals. Thus, they are considered an essential for well-balanced human diet. Additionally, they have been associated with improvements to reduce heart disease risk, cancer, stroke, chronic diseases, good vision and gastrointestinal health (Waliyar et al. 2010). According to FAO statistics, the global vegetable production in 2007 was almost nine hundred million tons (FAO 2009). Asia produced 74.7% of the total world vegetables on 72.8% of the world's vegetable production area. Among Asian countries, China has always been a large contributor (50%) to global vegetable production. The second largest contributor for vegetable production is India and almost six fold lower than China. The area under vegetable production is increasing at 2.8% annually which is higher than other crops like fruits (1.75%), oil crops (1.47%), root crops (0.44%) and pulses (0.39%) (FAO 2009). The consumption of vegetables in diet varies widely with geographic regions, nationality, local customs, availability of food variety and cuisine. In Asia, vegetables are consumed in the area where they produced. The largest producer and consumer countries include China, India, Bangladesh, Cambodia, Vietnam, Laos, and the Philippines (Gale 2002). The per-capita consumption of vegetables has increased from 41 to 141 kg in Asia between 1975 and 2003 (FAO 2009).

Agriculture industry is mainstay of Pakistan's economy and contributes more than twenty percent in GDP (gross domestic product) and it employs more than 43 percent of total labor force. A vast majority of Pakistani people (67.5%) are directly or indirectly connected with agriculture. Thus, any technological improvement or productivity enhancement in agriculture contributes to overall economic growth and also provides immediate benefits for a large number rural population. On the other hand, Pakistan Horticulture Development & Export Board (PHDEB) reported that horticulture sector share is about 12 percent in GDP. However, its growth is restrained by multiple factors e.g., lack of proper postharvest management, transport system, storage conditions, infrastructure. Almost, 13.67 million tons of fruits and vegetables are produced annually in Pakistan. Twenty-five percent of that amount goes to waste between farms to consumers while only 4% is exported at far lower price of about 41% less than the world average price of the same commodity.

In agriculture, the horticultural crops; especially vegetables have significant importance and contribute in national economy. Vegetables are a great source of income as well as important for food security for the people of Pakistan. In Pakistan, the area devoted for vegetable production is about 0.34 million hectares with total production of 4.8 million tons of vegetables. Pakistan exports vegetables across the world, including Middle East and South Asia. In 2004-05, the increase in foreign exchange was 17% higher than the previous year (2003-04). Major importers of Pakistani fruits and vegetables were Dubai, India, Afghanistan, Saudi Arabia, and the United Kingdom (UK). Another study reveals that vegetable area and production has increased by 21 and 13 percent respectively in Pakistan from 1990-91 to 2007-08.

During the last decades, the drastic increase of chemicals use for vegetable production has been observed leading to both direct and indirect costs to farmers and the society. These pesticides are causing a wide range of acute poisoning incidences among farmers (Maria et al. 2006; Recena and Pires 2006; Travisi and Nijkamp 2008). According to World Health Organization (WHO) more than three million cases of pesticide poisoning occur with 220,000 deaths at global level (Pimentel and Acquay 1992; Kishi and Hirschhorn 1995; Dasgupta and Mamingi 2001). During the last two decades, the amount of pesticides use for vegetable production has increased from 20213 metric ton to 94265 metric tons in Pakistan which accounts for a 366 percent increase. Thus, the expenditure becomes double from 5536 to 10534 million rupees in last two decades. Similarly, there was a 91 percent increase (1884 thousand tones to 3581 thousand tones) in fertilizer use during the same period. These facts clearly indicate the increase in chemical use for vegetable production. The intensive use of agro-chemicals affects the life on soil, water, and air due the associated environmental health hazards. In addition, the residues of these chemicals are also affecting the export of vegetables. The proper management of these chemicals with other limiting factors (abiotic and biotic) can increase the protection and production of vegetables which can help to increase the profitability of vegetable industry in Pakistan. In this way, the vegetable industry will help feeding the population in Pakistan, as well as in all developed and developing countries of the planet earth.

6.3. Classification of vegetables crops

The main or bold facts which one needs first to know about a vegetable he would cultivate are these: (1) whether root crop, leaf crop, fruit crop; (2) demands as to season or climate,—cold- weather crop or warm weather crop; (3) duration of its growth,—early or quick crop, full-season crop, catch-crop, companion crop; (4) whether to be transplanted or not; (5) to be grown in hills or drills and (6) the special demands as to soil and plant food (Bailey 1921). The other things to know are the peculiar treatments the crop demands in tillage and other special care, the enemies of the crop as well as their control and also the means of harvesting and marketing.

In the analysis of the methods of cultivating crops is a classification of the crops themselves. The classification of plants with reference to climate or season is very important for a cultivator. Some vegetables are known to be essentially hot-season or semi-tropical plants and can be injured or killed by frost. These include corn, tomato, cucumber, all melons, squashes and pumpkins, beans, okra, eggplant, red pepper or capsicum and sweet potato. They are commonly classed as "tender vegetables”. They should not be set in the open until danger of frost is past. The other type of vegetables are called cool -season or mid- temperate plants and are classed as "hard vegetables" since, when properly grown and handled, they can withstand considerable frost. These vegetables include all root crops, potato, all onion-like plants, pea, spinach, all cole crops, lettuce, asparagus and rhubarb. The vegetables are mainly classified as given in Table 6.1 (Bailey 1921; Nonnecke 1989).

6.4. Insect pests of major vegetable crops and their management

A pest is an anthropogenic designation instead of a biological phenomenon. For example, termites are considered beneficial organisms when they convert dead material into soil organic matter in forests while they are also become pests when they feed on wood-associated human structure. The insect is said to be an aesthetic or cosmetic pest while when insect decrease the value of a commodity they said to be economic pests. In case of vegetables, there is no absolute difference between aesthetic and economic injury due to insects. For example, a vegetable grower may consider a dimple (aesthetic injury) on tomato due to stink bug insignificant, while the same type of damage can cause buyer to down grade the value of the produce (economic loss) (Capinera 2001). Similarly the pests could be direct (attack the vegetable plant part harvested for food) or indirect (attack plant part that is not harvested). Insects cause different type of injuries and some species are capable of causing more than one type of damage. They can be divided into chewing insects and sucking insects depending upon their mode of damage.

The pest infestation largely depends upon the climatic conditions and the crops grown. Globally, there are more than 10,000 species of insects, 30,000 weeds, 100,000 diseases (cause by fungi, viruses, bacteria and other microorganisms) and 1000 species of nematodes which are responsible for food plant damage (Hall 1995; Dhaliwal 2007), while, less than 10 percent of total identified pests are considered major pests of crops. Insect pests and plant pathogens cause $30–50 billion of crop losses worldwide every year (Cook 2006). In case of insects, only one percent of total insects are considered as pests (Dhaliwal and Jindal 2010). The major insect pests of different vegetables are given in the table (Table 6.2) and few of them has been described below in detail.

6.4.1. Melon fruit fly

Technical name: *Bactrocera cucurbitae* (Coquillett)

Family: Tephritidae

Order: Diptera

Fig. 6.1 Melon fruit fly *Bactrocera cucurbitae* C. (Photo credit: A. Nawaz, UAF)

Biology

Distribution and host range

Melon fruit Fly is the most destructive and commonest pest of cucurbits and musk-melon. It is widely distributed in all the vegetable growing areas of Pakistan, India, Malaysia, Myanmar, China, Taiwan, Japan, Australia, East Africa, and Hawaii Island. The Asian parts of the range of this species represent its natural (native) range. In Hawaii, it is known to be an introduction, having arrived there late in the 19th century. Old records for Australia derive from an eradicated outbreak in, but as no specimens could be traced this may have been based on a misidentification of *Bactrocera chorista*. In Africa, *B. cucurbitae* is found in several countries in East and West Africa, including Benin, Burkina Faso, Cameroon, Gambia, Guinea, Ivory Coast, Mali, Niger, Nigeria, Senegal and Togo in West Africa, and Kenya, Sudan, Tanzania and Uganda in East Africa.

Besides melon, it is also found on tomato, chilies, cauliflower, guava, citrus, pear, fig and other cucurbitaceous vegetables. Its attack is severe on the late sown melons that ripen after the monsoon rain start.

Description of Stages

Egg: Whitish yellow and cylindrical

Maggots: Maggots are legless and appear headless. They are dirty white wriggling organisms, thicker at one end and taper to point at the other end. When full-grown they measure about 9-10 mm in length and 2 mm wide in the middle.

Pupa: Barrel shaped and light yellow at first but later on turn dark brown. They convert into winged adults in 6-9 days in the rainy season and 3-4 weeks in the winter.

Adult: Adult flies are reddish brown with yellowish patches on the thorax and fuscous areas on the outer margins of wings.

Life cycle

This pest remains active throughout the year but life cycle is prolonged in the winter except November-February. Adult flies emerge from pupae in the morning hours and mate at dusk. It takes few days for eggs to mature inside the female body and start egg laying within 14 days. Flies live for about 14-54 days. Female lays about 58-95 eggs, which hatch in 1-9 days. Eggs are laid in young fruits with soft and tender skin. Total number of eggs laid by one female range from 60-120 in its life time. Maggots are full-grown in 3 days in the summer and 3 weeks in the winter. When full-grown, they reach a suitable place and pupate at about 5 cm depth in the soil. Pupal period lasts for 6-10 days (Fig. 6.2). It has 4-10 generations in a year

Damage

Damage is caused by the maggots only by feeding on the near -ripe fruits thus riddling them and polluting the pulp. It makes a small hole with its sharp ovipositor to lay a dozen eggs mostly in the evening hours. Then she cements the hole to make it water proof by releasing gummy secretion which solidifies to appear shiny brown resinous material. Maggots bore into the pulp by forming galleries and begin feeding on the pulp till fruit decay as the attacked fruit decays due to secondary bacterial infection. Such affected fruit fall to the ground and the full-fed maggots come out of the rotten fruit and move away in jumps of 12-20 cm through folding and unfolding the two ends of its elongated body. Thus they reach a suitable place in the soil for pupation and 'emergence to adults. These adults are responsible for the further attack on the healthy fruits present in other corner of the same orchard. The pest causes serious damage of melons and its attack may reach 100% after first shower of the monsoon. Likewise about 50% damage can be seen in other cucurbitaceous fruits.

Management

Cultural control

Bagging of fruit: Bagging of fruits with 2 layers of paper bags at 2 to 3 days intervals minimizes fruit fly infestation and increases the net returns by 40-58%.

Field sanitation: Thus, surface ploughing after crop harvesting is recommended to expose the pupae to the temperature extremes. It is done mainly for destruction of pupae in the soil. Moreover, heavy irrigation is also helpful. Regular collection and burial of the infested fruits at 2-3 feet depth in soil or their burning is helpful to control the pest.

Mechanical control

Parapheromone lures/cue-lure traps: Attraction of adult flies through trap of methyl eugenol is also effective.

Biological control

There are no reports on the successful use of bio-control agents against the melon fruit fly. But *Opius fletcheri* S. to be a dominant parasitoid of *B. cucurbitae*.

Genetic control

Male-sterile technique: In this technique, sterile males are released in the fields for mating with the wild females. Sterilization is accomplished through irradiation, chemo-sterilization, or by genetic manipulation. In sterile insect programs the terms 'sterility' or sterile insect' refer to the transmission of dominant lethal mutations that kill the progeny. The females either do not lay eggs or lay sterile eggs. Ultimately, the pest population can be eradicated by maintaining a barrier of sterile flies.

Chemical control

1. Trichlorphon (Dipterex 80 WP), 1500 g ha^{-1}.
2. Dichlorvos (Thunder 1' Nogos / Nuvan / Nokovos / Phosvit 100 EC), 625 ml ha^{-1}.

Bait spray on lower surface of leaves of maize plants grown as trap crop nearby with 50 ml Malathion 57 EC + 0.5 kg Gur or sugar/50 litre water ha^{-1} is effective for its control. It may be repeated at 7 days interval depending on the infestation.

6.4.2. Armyworm

Technical name: Spodoptera litura F., Spodoptera exegua H.

Family: Noctuidae

Order: Lepidoptera

Biology

Distribution and host range

Armyworm is among the notorious pests of many vegetables and its seasonal activity varies considerably according to climate and crop conditions. The most susceptible vegetable crops and other field crops are bean, broccoli, asparagus, cauliflower, celery, beet, chickpea, corn, cowpea, cabbage, eggplant, onion, pea, pepper, lettuce, potato, radish, sweet potato, tomato, turnip, spinach, alfalfa, corn, soybean, peanut, safflower, cotton, sorghum, tobacco and sugarbeet.

Description of stages

(i) Spodoptera litura F.

Eggs: Creamy to golden brown in color.

Larvae: Bright yellow stripes along the back and the sides and color varies from pale green to dark green, and then finally brown for the later instars or more mature forms.

Pupae: Light to dark brown in color.

Adult: Forewings are gray to reddish-brown while hind wings are grayish-white with grayish-brown margins (Fig. 6.3).

Fig. 6.3 Armyworm, *Spodoptera litura* F. (Photo credit: A. Nawaz, UAF)

(ii) Spodoptera exegua H.

Eggs: Greenish to white in color.

Larvae: Pale green or yellow in color during the 1st and 2nd instars, acquire pale stripes during the 3rd instar, darker dorsally during 4th instar but 5th instar are quite variable in appearance.

Pupae: Light brown in color.

Adult: Forewings are mottled gray and brown while hind wings are a more uniform gray or white color, and trimmed with a dark line at the margin.

Life Cycle

Armyworms are prolific and responsive to favorable conditions. Eggs are laid in clusters of 50 to 150 eggs per mass and usually covered with body hair scales and laid on the underside of the host plant leaf. Eggs usually hatch between 3-4 days and tiny caterpillars resume feeding at night. They feed for several weeks and then pupate in soil to emerge as adults within 10 days. . The pupa is light brown in color and measures about 15 to 20 mm in length. Thus, 3-5 generations are commonly produced each season. The armyworm remains active throughout the year in warm climates. The average life cycle will be completed in about 25-30 days (Fig. 6.4). Mating occurs soon after emergence of the moths, and oviposition begins within 2-3 days and the moths usually perish within 9-10 days of emergence.

Damage

Feed at night on succulent foliage and the caterpillars do the damage only. Young larvae of armyworm feed gregariously and skeletonize foliage leaving the veins of leaves largely intact. As feed at night, they can severely damage seedling stands and may inflict much injury before they are detected. The worms migrate as an "army" to new host plants.

Management

Biological control

The use of insect pathogens like nuclear polyhedrosis virus (NPV), *Beauveria bassiana* and nematodes (Rhabditida: Steinernematidae and Heterorhabditidae) are fairly effective as a bioinsecticide.

Chemicl control

Chlorpyrifos 40 EC (2500 ml ha^{-1}), Thiodicarb 80 DF (1 kg ha^{-1}), Acephate 75 SP (1.8 kg ha^{-1}), Spinosad 240 SC (200 ml ha^{-1}), Indoxacarb 150 SC (430 ml ha^{-1}) and Lufenuron 50 EC (250 ml ha^{-1}).

6.4.3. Brinjal fruit and shoot borer

Technical name: *Leucinodes orbonalis* G.

Family: Crambidae

Order: Lepidoptera

Biology

Distribution and host range

This pest is practically monophagous, however, other plants belonging to family Solanaceae are reported to be hosts of this pest. It enjoys a country wide distribution and besides, Pakistan it is also found in countries like India, Sri Lanka, Burma, Malaysia, Congo and South Africa.

Description of stages

Eggs: White and flat in appearance.

Larvae: Fully grown larvae are stout, pink with brown head.

Pupae: Pupate in a tough silken cocoon. The color and texture of the cocoon matches the surroundings making it difficult to detect.

Adult: Small white moth with 40-segmented antennae (Sexena 1965) and having spots on forewings (Fig. 6.5).

Fig. 6.5 Brinjal fruit and shoot borer, *L. orbonalis* G. (Photo credit: A. Nawaz, UAF)

Life Cycle

The female oviposit during the night on the lower surface of the young leaves, green stems, flower buds, or calyces of the fruits. Eggs are laid singly or in the batches and number of eggs laid by a female vary from 80 to 253. The larval period varies in summer (12-15 days) from winter (14-22 days) and larvae pass through at least five instars. The full-grown larvae pupate in the dried shoots, leaves or in plant debris within tough silken cocoons. The pupal period ranges from 6-17 days depending upon environmental conditions. Following emergence, the young adults are generally found on the lower leaf surfaces or under plant canopy. Adult become full mature in 10-14 days. The longevity of males and females lasts for 1.5 to 2.4 days and 2.0 to 3.9 days respectively. The adult male dies after mating and the female moth dies after laying eggs. The *L. orbonalis* has five generations a year and overall life cycle completes in 22-55 days (Fig. 6.6).

Damage

Brinjal fruit and shoot borer attacks mostly on flowering, fruiting and vegetative growing stage on fruits/pods, growing points and inflorescence. The intensity of attach by larvae is in fruits followed by shoots, flowers, flower buds and midrib of leaves (Alpuruto 1994). Damage to the fruits is very severe during autumn. *L. orbonalis* is active throughout the year at places having moderate climate.

Management

Cultural control

Pruning of infested twigs and branches prevents the dissemination of the pest. Similarly, the pest infestation can be reduces by periodic pinching/pruning of wilted damaged shoots, their collection and burrying or burning. In addition, the removal of the alternate food sources and use of mechanical barriers are some of the cultural and mechanical measures to prevent the pest infestation.

Sex pheromones

Sex pheromones are important component of IPM programs. Combination of chemicals (E)-11-hexadecenyl acetate and (E)-11-hexadecen-1-ol continuously trap high number of male moths on pheromone trap and significantly reduce the pest damage.

Biological control

The spore forming Bacillus spp. has been most important in insect suppression. No doubt, the efficacy NPV against *L. orbonalis* is lower but it can be used as one of the important options of management. There are sixteen parasitoids, three predators and three species of entomopathogens have been reported as natural enemies of *L. orbonalis* from all over the world which can be used as effective biocontrol agents.

Chemicl control

Betacyfluthrin 25 EC (500 ml ha^{-1}), Lufenuron 50 EC (500 ml ha^{-1}) and Cypermethrin 10 EC (625 ml ha^{-1}) can be used for effective control of brinjal fruit and shoot borer. Emamectin Benzoate, Methoxyfenozide and *Bacillus thuringiensis*

(Berliner) also performed well in reducing damage and increasing yield (Chatterjee and Mondal 2012).

6.4.4. Red pumpkin beetle

Technical name: *Aulacophora foveicollis* L.

Family: Chrysomelidae

Order: Coleoptera

Biology

Distribution and host range

The pest is the most destructive pest of all cucurbitaceous vegetables and widely distributed in different regions of the world like Asia, Africa, Australia and South Europe. It occurs throughout the country in. The *A. foveicollis* is the commonest beetle found in Pakistan and infests a wide variety of vegetables like pumpkin, tinda, melon, ghia tori, cucumber etc., but have special liking for pumpkin.

Description of stages

Eggs: Elongated and brown in colour.

Larvae: Whitish grubs with brown head bores.

Pupae: Exarate types of pupae with naked appendages. Its changes its color to yellowish with red eyes when it is fully-developed.

Adult: Beetle is deep orange on dorsal side, while the ventral side is black and abdomen bears soft white hairs posteriorly (Fig. 6.7).

Fig. 6.7 Red pumplkin beetle *A. foveicollis* L. (Photo credit: A. Nawaz, UAF)

Life Cycle

After mating, female lay 300 egg's singly or in batches (8-9) in the moist soil of the host plant base. The larvae hatch after 6-15 days. The whitish grub feed upon plant roots, fallen leaves and fruits lying on the surface of soil. Larval stage lasts for 13-25 days. Fully grown grubs pupate (7-17 days) in soil within a water-proof, thick walled oval cocoon. After metamorphosis, the adult beetle comes out of soil to feed and to breed. Beetle start laying eggs after about seven days of emergence. The pest complete five generations in a year. A complete life cycle takes about 25-37 days (Fig. 6.8). The adult beetles hibernate inside soil or among dry weeds.

Damage

A. foveicollis is polyphagous and attacks more than 81 plant species including pumpkin and a wide range of fruit crops. The damage is caused mainly by the adult insects which feed voraciously on the leaves, flowerbuds and fruits. The young ones (grubs) of this pest remain in the soil and damage roots and stem of the plant.

Management

Cultural control

Few scattered trap crop plants should be grown and treated with strong insecticidal spray. Similarly, the soil around the root of the plant should be sprayed with strong insecticides for the control of developing grubs and pupa.

Mechanical control

During the early hours of morning, the beetles remain sluggish so they can be collected and killed in kerosene oil.

Biological control

The entomopathogen *Serratia marcescens* killed high percentages of adult when smeared on bodies. The fungus *Fusarium moniliforme* subglutinans killed all infected adult of *A. foveicollis* in an average of 4 days. Similarly, *A. foveicollis* is highly susceptible to entomopathogenic nematode *Steinernema feltiae* when fed on foliage sprayed with suspensions of the nematode. However, no practical field applications of biocontrol agents proved to be successful against this pest.

Chemical control

The chemical insecticides such as Deltamethrin 2.5 EC (625 ml ha^{-1}), Carbaryl 10 D (12.5 kg ha^{-1}), 5% Malathion (10 kg ha^{-1}), HGW86 10 OD (105 g ha^{-1}) and Spinosad 45 SC (56 g ha^{-1}) can be used for effective control of red pumpkin beetle.

6.4.5. Hadda beetle

Technical name: *Henosepilachna vigintioctopunctata* F. or *Epilachna vigintioctopunctata* F.

Family: Coccinellidae

Order: Coleoptera

Biology

Distribution and host range

H. vigintioctopunctata is native to southeastern Asia, but has been accidentally introduced to other parts of the world, including Australia, New Zealand, Brazil and Argentina. It causes damage primarily in the family Solanaceae, especially potatoes while the other host crops include pumpkin, turnips, brinjal, datura, radishes, beans, tomato and spinach.

Description of stages

Eggs: Elongated and yellow coloured.

Larvae: Grubs are oval, fleshy yellow, with six rows branched spines.

Pupae: Oval in shape and dark in colour.

Adult: Beetle deep yellowish reddish coloured with black spots on the forewings (Fig. 6.9).

Fig. 6.9 Hadda Beetle, *E. vigintioctopunctata* F. (Photo credit: A. Nawaz, UAF)

Life Cycle

Female lay about 120-180 eggs in the cluster of 40-45. Female laid eggs on lower surface of the leaves and are arranged side to side on the surface of the leave in erect position. The larva hatches in 3-4 and 4-9 days in summer and winter months respectively. The larval period may prolong up to 15-32 days depending upon the host. The grubs feed to the epidermis of the leaves. The larva changes into pupa after 9-18 days of larval period during which it passes through four different instars. The pupal period lasts for 3-6 days (Fig. 6.10) and the last larval skin acts as pupal case. In summer, the life cycle is completed in 17-18 days which may prolong to 50 days in winter. The total number of generation may be around 7-8 in a year. The adults can survive up to 1-2 months.

Damage

Both adults and immature cause damage by scraping out the chlorophyll and feeding on the green tissues of the leaves and skeletonizing them. The leaves ultimately turn brown, dry up and fall off. In case of severe attack, the crop gets completely defoliated.

Management

Cultural control

Thorough irrigation of infested crop can minimize the increase in pest population.

Mechanical control

In green house cultivation, the larvae and eggs can be hand collected and destroyed or buried.

Biological control

There are a number of parasitoids to parasitize the different stages of beetle. They can be used a biocontrol agents. For example, *Tetrastichus ovulorum* F. and *Achrysocharis appannai* used to parasitize the eggs of hadda beetle. The *Solindenia vermai*, *Pleurotropis epilachinae*, *Tetrastichus sps*, *Uga menoni*, can be used against grubs while pupa is parasitized by *Pleurotropis foveolatus*. The entomopathogen (*Beauveria bassiana*) based biopesticides can also be used to control this pest which can help to reduce the spray load of insecticides on vegetables and to minimize the pesticide hazards to the consumers.

Chemical control

The insecticides such as Cypermethrin + Curacron 440 EC (1250 ml ha^{-1}), Carbaryl 10 D (12.5 kg ha^{-1}), Malathion 57 EC (1800 ml ha^{-1}) and Spinosad 45 SC (56 g ha^{-1}) can be used for effective control of hadda beetle. Spraying Calcium arsonate and Lime carbaryl (0.1%), Parathion (0.025%), Malathion (0.1%), Fenitrothion (0.05%) is quite effective in keeping the pest population under control.

6.4.6. Whitefly

Technical name: *Bemisia tabaci* G.

Family: Aleyrodidae

Order: Hemiptera

Biology

Distribution and host range

Whitefly may attack more than 500 plants species which includes avocado, cauliflower, cabbage, waxgourd, cucumber, brinjal, okra, fig, green bean, guava, lettuce, pumpkin, rose, soy bean, squash, sweet potato, tomato and watermelon. There are about 1000 species of whitefly in the world. Whitefly is a serious pest of cultivated crops in tropical and subtropical areas including Africa, Asia, Central America, South America, and the West Indies.

Description of stages

Egg: Smooth surface, elliptical and yellow in colour.

Nymphs: Scale-like and inactive having three nymphal stages. Nymphs are creamy white to light green in color.

Adult: Small in size and pale yellow in colour with two pairs of white wings which are covered with white waxy powder (Fig. 6.11).

Fig. 6.11 Whitefly, *Bimisia tabaci* G. (Reproduced with permission by: http://www.invasive.org)

Life cycle

Whitefly has six life stages as egg, four nymphal stages, and the adult. The life cycle period varies with temperature. The favorable temperature range is between 10 to 32°C. The female lays 100-120 eggs on the underside of the leaves. After 7 days, the nymphs emerge and attach to one place on the leaves to feed and become pale green or creamy flattened scale-like bodies. The pupal stage starts after 3rd moults and known as pseudo pupa. It completes its one generation in 2 to 4 weeks depending on temperature (Fig. 6.12).

Damage

Whiteflies are sap sucking insects and feed into the phloem of plants. They inject poisonous saliva due to which turgor pressure decreases. Indirect losses may occur due to the development of sooty mold fungus on honey dew secretion of Whitefly. The symptoms include sticky film appears on the leaves, yellowing of leaves ultimately growth of plants are stunted.

Management

Cultural control

Field sanitation and use of insect-free seed for sowing, crop rotation, cleaning of fields could be helpful for the management of thi pest.

Biological control

The parasitic wasp *Encarsia formosa* is generally used as biological control agent against whitefly, while some species can also control by coccinellid beetles, lacewings, flies, ants and mites also prey on them.

Chemical control

The Pesticides like Polo 500 SC (625 ml ha^{-1}), Confidor 200 SL (625 ml ha^{-1}), Mospilan 20 SP (200 g ha^{-1}) and Danitol 30 EC (500 ml ha^{-1}) can be used for effective control of whitefly.

6.4.7. Aphid

Technical name:	*Aphis gosssypii* G.
Family:	Aphididae
Order:	Hemiptera

Biology

Distribution and host range

Aphids are found everywhere in the world. They have ability to migrate long distances by mean of winds. They can also been spread by human transportation or infested plant materials. It is distributed throughout cotton growing areas of the world. It is common in North and South America, Central Asia, Africa, Australia, Brazil, East Indies, Mexico and Hawaii and in most of Europe. The host plant of this pest belongs to different agricultural crops in the families Cucurbitaceae, Rutaceae and Malvaceae. The cucurbit vegetables attacked by aphid are watermelons, cucumbers, cantaloupes, squash and pumpkin. In addition, other vegetable crops like pepper, eggplant, okra and asparagus etc. are also seriously affected by this pest.

Fig. 6.13 Aphid, *Aphis gossypii* G. (Reproduced with permission by: http://www.invasive.org

Description of stages

Egg: Elliptical and yellow or greenish in color.

Nymphs: Scale-like and inactive. Nymphs are brown to green in color.

Adult: Small in size and may or may not have wings. Wingless adults are yellowish green (Fig. 6.13) while winged adults are blackish green.

Life cycle

Aphids are generally produced parthenogenetically (viviparously). Adult female can give 12 live offspring per day without mating (Fig. 6.14). Parthenogenetically produced offsprings are known as nymphs. They shed their skin four times before becoming adults which last for 7-10 days. There is no pupal stage. Late in the season, both males and egg-laying (oviparous) females are produced. They mate and females deposit yellow eggs which help for overwintering under cold conditions. When the weather is warm, many species of aphids can develop from newborn nymph to reproducing adult in 7-8 days. Aphid populations can increase with great speed because a single adult female aphid can produce up to 80-100 offspring in a matter of a week.

Damage

Heavy aphid infestation may cause turning of leaves, yellowing and stunting of shoots. Aphid honeydew encourages the growth of sooty mold fungus that causes indirect damage. Some aphid species inject a toxin into plants, which causes leaves to curl and further distorts growth. A few species cause gall formations. They also act as vector of transmitting viruses (Cucumber mosaic virus, watermelon mosaic virus and zucchini yellow mosaic virus) from plant to plant on certain vegetable and ornamental plants. Squash, cucumber, pumpkin, melon, bean, potato, lettuce and beet, are crops that often attacked by aphid. The viruses cause yellowing or curling of leaves and ultimately plant growth stopped. In case of heavy infestations they may also attack on roots and kill them such as in carrots.

Management

Cultural control

Before planting vegetables removal of weeds and alternates hosts. Avoid high levels of nitrogen fertilizer application as it favor aphid reproduction. Reduce losses by growing seedlings under defensive covers in a greenhouse, or inside and then transplanting them when the seedlings are older and more tolerant of aphid feeding.

Mechanical control

The use of yellow sticky traps can be very helpful to control aphids.

Biological control

Aphid can be controlled by natural enemies such as parasitic wasps. After parasitization aphid's skin turns into golden brown and become mummified. Many predatory insects which can be used to control aphids are lady beetle adults and larvae, lacewing larvae, soldier beetles, and syrphid fly larvae.

Chemical control

The insecticides such as Acetamaprid 20 SP (300 g ha^{-1}), Carbusalfan 20 EC (1250 ml ha^{-1}), Difenthioran 500 SC (500 ml ha^{-1}) and Imidacloprid 200 SL (200 ml ha^{-1}) etc. can be used to control aphid.

6.4.8. Vegetable weevil

Technical name: *Listroderes costirostris obliquus* K.

Family: Curculionidae

Order: Coleoptera

Biology

Distribution and host range

The vegetable weevil has South American origin. It is now causing damage to many crops in different regions like Gulf, Oklahoma, Arizona, and California. The major host vegetable crops are carrot, turnip, mustard, collard, tomato, tobacco, potato and also a lot of weeds.

Description of stages

Egg: Elliptical and creamy white in appearance when laid then turn black before hatch.

Larvae: Pale green, legless as a dark mottled head when fully developed.

Pupa: Appears pale yellow and turns brown later.

Adult: Dull grayish-brown with a light V-shaped mark on the wing covers and have a short snout (Fig. 6.15).

Life Cycle

The adults remain active during winter, and spring seasons. This pest aestivates in trash, leaves or grass at the edges of fields during the summer season. They reproduce parthenogenentically. The hatching process occurs after an incubation period of 2 or more weeks depending on the environmental conditions. Larvae feed on seedlings and become fully grown in 23-45 days. Pupation takes place in soil during spring or in fall. Adults emerge from January to June. The length of time from egg hatch to adult emergence may vary from 1 to 4 months (Fig. 6.16). There is one generation per year.

Damage

Larva and adult weevils attack the roots and foliage of a number of vegetable crops. Larvae feed on the buds and the leaves of seedlings. Their feeding causes irregularly shaped holes in the leaves.

Management

Cultural control

Alternate cropping with non-host plants and weed-free fallow fields prior to planting can minimize the damage caused by vegetable weevil. Similarly, some plants contain or give off compounds that repel insects. Therefore, planting garlic among vegetables helps to deter vegetable weevils. In Addition, removing crop debris and soil cultivation/tillage after harvest will destroy pupae in the soil and reduce their survival during the hot months.

Biological control

Currently, no commercial biological control agents are available for vegetable weevil. But the use of neem oil and pyrethrins are options for organic control of this pest.

Chemical control

In case of heavy infestation, dust plants with a small amount of diatomaceous earth can minimize the damage. Match 50 EC (500 ml ha^{-1}) Karate 2.5 EC (1000 ml ha^{-1}) and Tracer 240 SC (100 ml ha^{-1}) are also very effective for the control of brinjal fruit and shoot borer. Spot treatment of foliage for vegetable weevil can also be economical. The use of insecticides mixture with azadirachtin or pyrethrin can often provide sufficient control.

Fig. 6.15 Vegetable weevil, *L. costirostris obliquus* K. (Reproduced with permission by: http://www.invasive.org)

6.4.9. Cabbage butterfly

Technical name: *Pieris brassicae* L.

Famliy: Pieridae

Order: Lepidoptera

Distribution and host range

The cabbage butterfly is common across North America, Europe, North Africa and Asia even through the Himalayas. It also occurs in Australia and New Zealand.

Cabbage butterfly is not found in desert and semi-desert regions (except for irrigated areas). This pest can be found in any open area with diverse plant population. It is also present in towns, natural habitats and mostly in valleys. Larvae of this insect feed widely on plants in the family Cruciferae. The main host of cabbage butterfly is cabbage at larval stage while adult butterflies suck nectar from flowers. Other than cabbage, commonly attacked are vegetable crops such as broccoli, Brussels sprouts, cabbage, cauliflower, collard, horseradish, kale, and kohlrabi.

Description of stages

Eggs: pale-white or yellow and change to bright orange prior to hatching. They are ribbed vertically and laid upright in clusters of 40-100.

Larvae: Newly-emerged larvae are yellow in color and changes to yellowish-green after the first moult. The heads are shiny black.

Pupae: Pale green or greyish-white and dotted with black and yellow markings.

Adults: Females are larger in size than the males. Adult wingspan is around 55-70 mm. The wing upper sides of both sexes are usually gleaming white with a pronounced black tip to the forewing. Female has a pair of post-discal black spots on the upper side of forewing while male has black spots on the lower side of forewings (Fig 6.16).

Fig. 6.16 Cabbage butterfly, *Pleris brassicar* L. (Phot credit: A. Nawaz, UAF)

Life cycle

The life cycle completes within 3-6 weeks depending upon the environmental conditions. Female oviposit eggs in bunches on the undersides of leaves. They use the tip of the abdomen and arrange the eggs in specific batches. The pre-oviposition period lasts for 7-8 days during which the female mate with males. They oviposit approximately six to seven times in eight days. The cabbage butterfly remains active throughout the year. The optimum activity of the pest is in November-December and March-April. Female lay eggs in cluster and eggs hatch out in 5-15 days depending upon the environmental conditions. The larvae feed gregariously and complete five instars in 20-30 days during different seasons. The pupal stage lasts 6-12 days in

March-April and 20-25 days November-February. They have around four generations in a year.

Damage

The caterpillars of cabbage butterfly feed on foliage, and if left unchecked often will reduce mature plants to stems and large veins. They prefer leafy foliage but during heavy infestation the caterpillars may burrow into the heads of broccoli and cabbage, especially as they mature. The caterpillars are often difficult to dislodge and overlooked. The caterpillars produce large quantities of fecal material which also cause contamination of the produce. The size of the affected heads reduced and sold at a lower price in the market. Damage to cabbage heads has been reported to be as high as 70-98%.

Management

Cultural control

The use of resistant varieties can reduce the attack of cabbage butterfly. In addition, the collection and destruction of adult butterflies through hand nets could also be effective. The handpicking and destruction of larvae at early stage can also minimize the damage.

Biological control

The natural enemies of cabbage butterfly can be introduced in the field for the biological control of this pest. Parasites like Apanteles sp., braconid and tachonid fly parasitizes the cabbage butterfly caterpillars. The predators like lady beetle and lacewing also effectively reduce the pest attack in the field. There should be minimum use of pesticides in the field for best control of pest through biocontrol agents. In addition, the use of biopesticides Btk (Bacillus thuringiensis kurstaki) can be effectively used to controls this pest.

Chemical control

The insecticides such as Lufenuron 50 EC (500 ml ha^{-1}), Cypermethrin 10 EC (500 ml ha^{-1}), Chlorpyrifos 40 EC (1250 ml ha^{-1}), Deltamethrin 2.5 EC (500 ml ha^{-1}) and Spinosad 240 SC (200 ml ha^{-1}) can be used for effective management of cabbage butterfly.

6.5. Different approaches for insect pests management

6.5.1. Biodiversity management

Biodiversity is the variety of plants, animals, and microorganisms on planet Earth and provides protection from pest attack through creating balance of life in the environment. The consequences of conventional agricultural practices (burning of crop residues, continuous ploughing and harrowing, deforestation, overgrazing, mono-cropping, misuse of pesticides, excessive use of fertilizers and misuse of water) are loss of soil fertility, food insecurity, health risks, soil and surface water contamination, greenhouse gas release, pest invasion, and loss of biodiversity (Bot and Benites 2001). The biodiversity of both plants and insects in the field can play an important role in pest management through top down and bottom up approaches (Gratton and Denno 2003).

Plant diversity has had a positive impact on herbivore insects by favoring associated natural enemies as it is evident that increased parasitism was observed in flowering plants (Thies and Tscharntke 1999; Vandermeer 1995). These plants provide pollen and nectar, which are important for normal fecundity and longevity of parasitoids. In addition, the flowering plants also attract non-herbivore insects which serve as food for insect predators. Wild vegetation around crops also enhanced biological control (Leius 1967). Similarly, Insect biodiversity represents a large proportion of world biodiversity and is indivisibly linked with agriculture due to large surface area under agriculture. In recent decades, awareness on the role of predatory arthropods in controlling insect pests has increased (Thorbek and Bilde 2004; Scudder 2009). Besides that, weeds play an important role in agriculture production. They can limit the positive impact of chemical, physical and cultural control measures. Even herbicides temporarily suppress a particular group of weeds. Consequently, biological control of weeds through their natural enemies (insects and microorganisms) is attractive and practical. There are a number of insects and microorganisms which feed specifically on weeds (Baloch 1974; Goeden and Andres 1999; Evans 2002). Conclusively, the biodiversity conservation of insects and plants will play a very important role for the production and protection of vegetables as well as for other crops.

6.5.2. Integrated pest management (IPM)

IPM is a "decision-based process involving coordinated use of multiple tactics for optimizing the control of all classes of pests in an ecological and economical sound manner" (Prokopy 2003). It involves managing multiple pests simultaneously, monitoring of pests and their natural enemies, and integration of multiple control tactics. The ultimate objective of this approach is to reduce the use of pesticides, provide economic savings to farmers, and protect the environment and human health. The multiple tactics used in IPM include cultural control, mechanical control, physical control, biological control, and chemical control. These control measures are adopted according to the requirement in the field.

No doubt IPM is a potential management practice but there is little evidence that these management practices have been implemented to a significant extent in agriculture all over the world (Barfield and Swisher 1994; Morse and Buhler 1997; Ehler and Bottrell 2000). There are three main constraints of this failure. First of all, IPM is time consuming, complicated for farmers, and has multiple demands for farm production to carry out integration of multiple control tactics for all classes of insects. Second, the pest control consultants who might be hired by farmers or employed by pesticide companies. These consultants usually have little time for close monitoring of pests or have a conflict of interest due to pesticide companies. Finally, the scientists working in the land-grant agriculture universities or colleges who mostly working to study the individual ingredients of IPM and this are reinforced by the incentive system in which they work. Another term for IPM now is used as

"Integrated Pesticide Management" with ultimate objective to reduce the pesticides to avoid their health hazards on human health and the environment (Birch et al. 2011). In the future, IPM is expected to be a dominant theme in agriculture which includes the increased use of reduced risk pesticides and genetically engineered crops.

6.5.3. Biointensive IPM (BIPM)

The cost of cultivation is an important factor for crops grown in a resource-poor environment. Therefore, pest management should naturally regulate pests and diseases in any given field. The term biointensive integrated pest management (BIPM) is a more dynamic and ecologically-informed approach that considers the farm as a part of the agroecosystem. In order to minimize pest damage, BIPM particular characters need to be understood (Reddy 2013) because it emphasizes the importance of ecological basis of pest infestations. Thus, BIPM reduces chemical use and costs of conventional IPM. It requires that the agricultural system be redesigned to favor natural enemies of pests and to actively disadvantage pests, e.g. implementing polyculture instead of monoculture.

6.5.4. Precision agriculture for vegetable production

The use of fertilizer also influences the insect pest infestation (Yardım and Edwards 2003). While conventional agricultural practices mostly ignore the uniform application of practices across the field during fertilizer application. Therefore, the variation in soil properties is common rather than the exception (Mulla 1997). Precision agriculture or information-based management of agricultural production systems consists of geo-referenced data collection. This data provide relevant information for management planning. Predictive and reactive approaches can be used to apply inputs in the vegetable field. These approaches are mainly used for fertilizer application (nitrogen), agrochemical and water management (Heege 2008). The next step is the use of auto-guidance systems and autonomous agricultural vehicles for crop production but safety and liability have halted their adoption. Precision agriculture can be applied to manage the problems of vegetable production but fundamentally needs information on field variability which is not always easy to obtain. In recent years, advances in different technologies such as GPS (Global Positioning System), GIS (Geographic Information Systems), RS (remote sensing) and SD (simulation modeling) are making it possible to assess spatial and temporal variability in a field including site-specific management practices (García-Torres et al. 2003).

Though, precision agriculture is technology dependent, it could be helpful vegetable farming practices. By adopting the best agriculture land management practices for each area, we can implement vegetable cropping on a larger scale, as the ultimate basic objectives of precision agriculture is natural resource conservation and productivity maintenance.

6.5.5. Biotechnology and insect pest management

To feed the growing world population, the control of herbivorous insect pests and plant diseases is essential. Biotechnology and genetic engineering helps to generate resistance against pests (insect pests, pathogens). Following are the major implementations of biotechnology to increase production by protecting crops from insect pests.

6.5.5.1. Insect peptides

A number of peptides or proteins have anti-pest infection activity, like microbial peptides from the bacterium *Bacillus thuringiensis* (Berliner) show activity against various insects (Tabashnik *et al.* 2008, James, 2008). Currently, to increase the potential of anti-pest peptides, the *Bt* peptides are being used in combination with other traits like herbicide resistance (Marcos et al. 2008). During the last decade a lot of progress was made to study the activity of lectins that are expressed in response to herbivory by phytophagous insects. Similarly, many plant species have entomotoxic proteins with high potential to use in pest control strategies based on their activity towards herbivorous insects (Killiny et al. 2012).

6.5.5.2. Ribonucleic acid interference (RNAi)

Transgenic crops that express *Bt* toxin technology protect crops against lepidopteran and coleopteran pests, but excluding many important dipteran and hemipteran pests like flies and true bugs (Toenniessen 2003). RNA interference technique (RNAi), discovered in the nematode *Caenorhabditis elegans,* is caused by exogenous double-stranded RNA (dsRNA). This technique down-regulate gene expression in a wide range of organisms by the RNAi effect, through a plant-delivered RNA which offers possibility of effective protection against any species. The genes which are necessary for survival, growth, development, reproduction or feeding success can be targeted through this technique. There are two reports published in recent years that showed feasibility of this technique to control insect pests (Mao 2007). Realizing the potential of this RNAi technology requires more research at both fundamental and applied levels. A more systematic approach to examining the factors like the stability of input RNA in the insect gut and diet, RNA transport across the insect gut etc., will lead to a better understanding of how to maximize the effects produced in insect pests through RNAi technique. This will help to control insect pests more effectively without negative effect on the environment.

6.5.5.3. Sterile insect technique (SIT)

Insect transgenesis can provide novel strategies for insect pest management. Particularly, the sterile insect technique (SIT) may be improved by using transgenic approaches. It is evident that this technique has been successfully applied for some species and considered environmentally-friendly alternative to insecticides (Dyck et al. 2005). SIT uses the release of mass-reared, sterile insects to cause infertile mating and ultimately reduces the pest population (Klassen and Curtis 2005). Biotechnology can be useful to optimize efficiency and reducing costs to transfer this effective technique to a wider range of species by improving mass-rearing, sex separation, sterilization and marking for monitoring. The success stories of SIT include the control of pink boll worm (*Pectinophora gossypiella,* Saunders) in California (Henneberry 2007), tsetse fly (Glossina austeni, Newstead) in Zanzibar (Vreysen 2000), new world screwworm (*Cochliomyia hominivorax,* Coquerel) in North and Central America and various tephritid fruit fly species in various regions of the world (Klassen and Curtis 2005). These technologies can be used in vegetable farming to manage insect pest populations without using toxic chemicals. It is also clear that a considerable research is needed on the use of GM (genetically modified) insects in the field to shun any harmful side effects on non-target organisms.

6.6. Conclusion and future perspectives

The vegetable industry can play an important role to manage the food security issue of the world, especially in developing countries. A number of factors are responsible for low production of vegetables such as biotic factors (vegetables and other crops in the field, weeds, insects, pathogens and natural enemies of vegetable pests), and abiotic factors (soil, water, temperature, light, humidity, wind, fertilizers and pesticide). In addition, the reluctance of producers to associate with vegetable farming organizations, lack of commercial arrangements between producers and vegetable dealers, low prices and poor quality produce, and use of unqualified labor also cause losses due to low production and poor marketing of vegetables. Postharvest losses are also greater than generally realized while passing vegetables from the field to consumers. These problems can be solved through integration of different control measures. The techniques which could be used to minimize the vegetable losses are biodiversity management at farm level, IPM, BIPM, use of precision agriculture technology for input application, postharvest handling, and marketing of vegetables. The careful use of biotechnology always has a definite advantage in increasing vegetable production by reducing crop losses and managing insect pests. This will help to increase vegetable production and minimize the health hazards of chemicals used to control the vegetable pests. To meet the growing challenges of vegetable industry in future, an effective integration of research and development sector (R&D), agricultural academic, and research and extension institutions should be established. This will help to meet the nutritional need of ever growing population of the world.

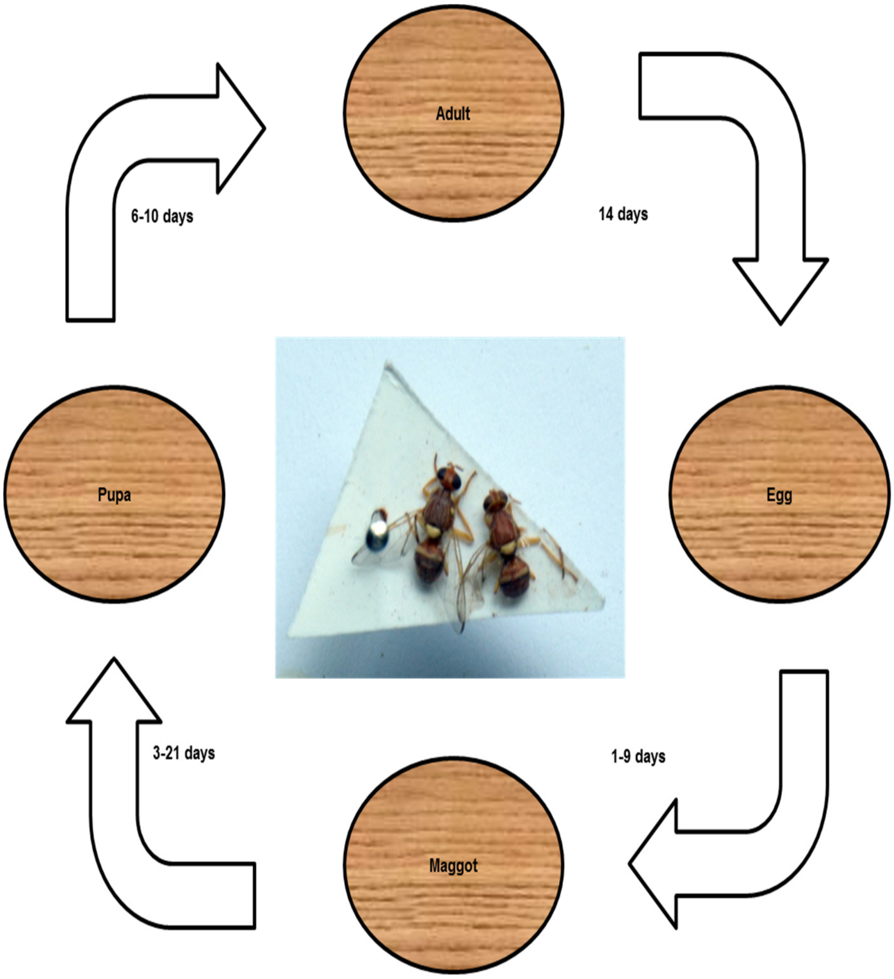

Fig. 6.17 Life cycle of melon fruit fly (*Bactrocera cucurbitae* C.)

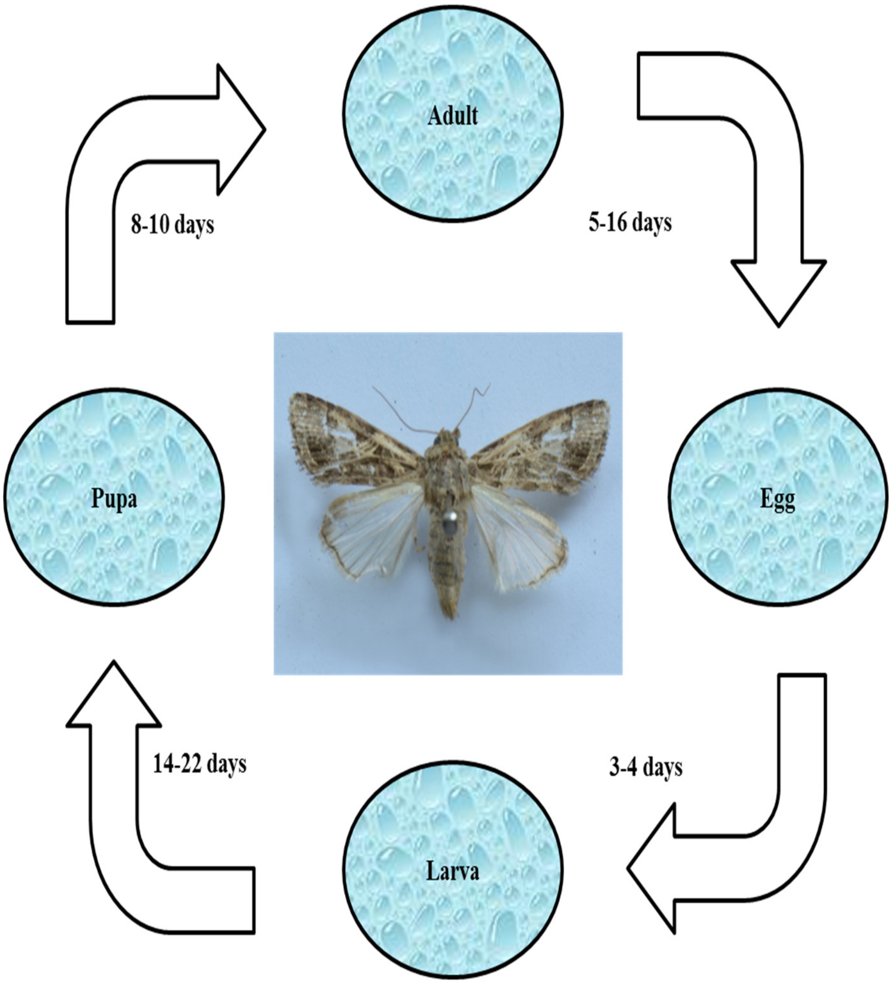

Fig. 6.18 Life cycle of armyworm (*Spodoptera litura* F.)

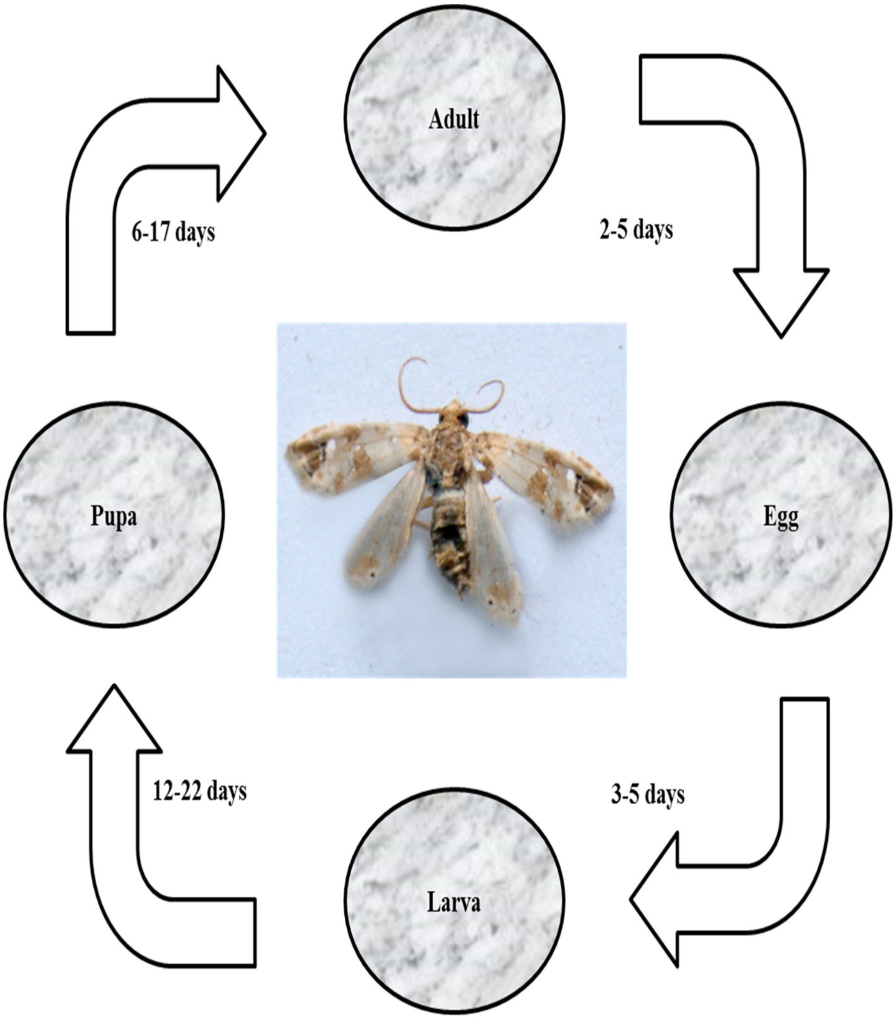

Fig. 6.19 Life cycle of brinjal fruit and shoot borer (*Leucinodes orbonalis* G.)

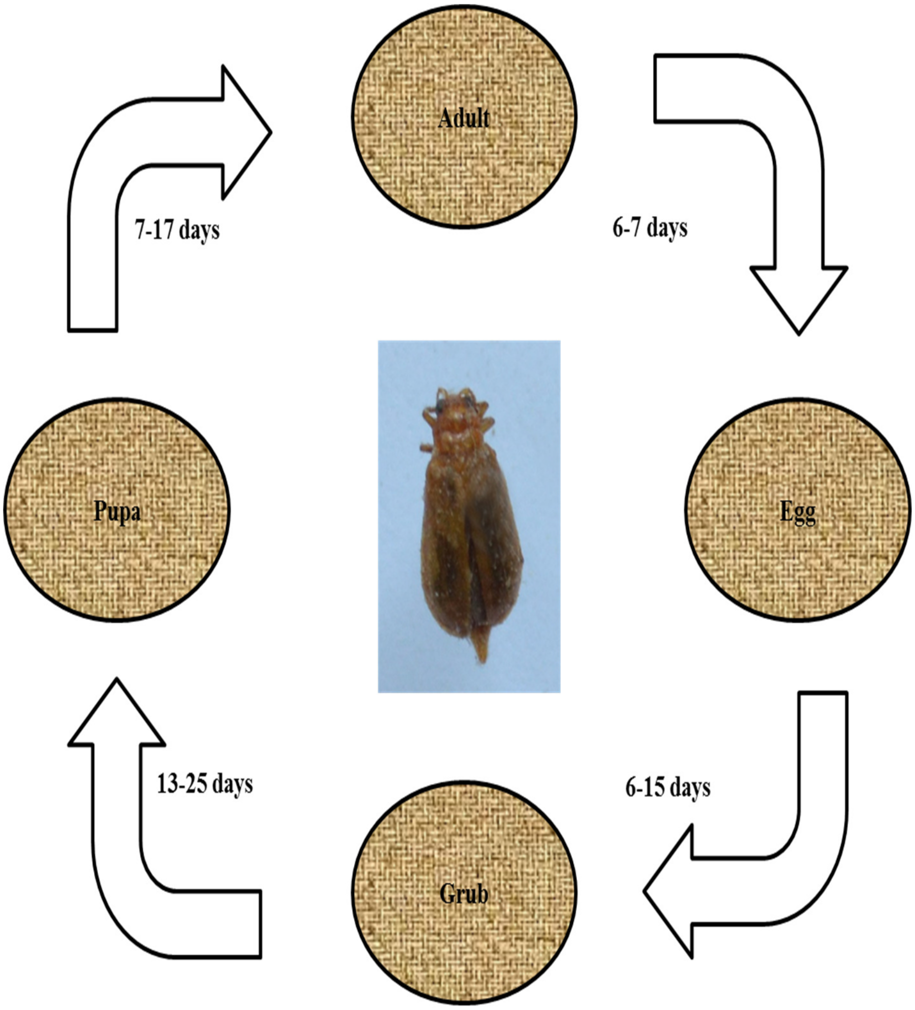

Fig. 6.20 Life cycle of brinjal fruit and shoot borer (*Leucinodes orbonalis* G.)

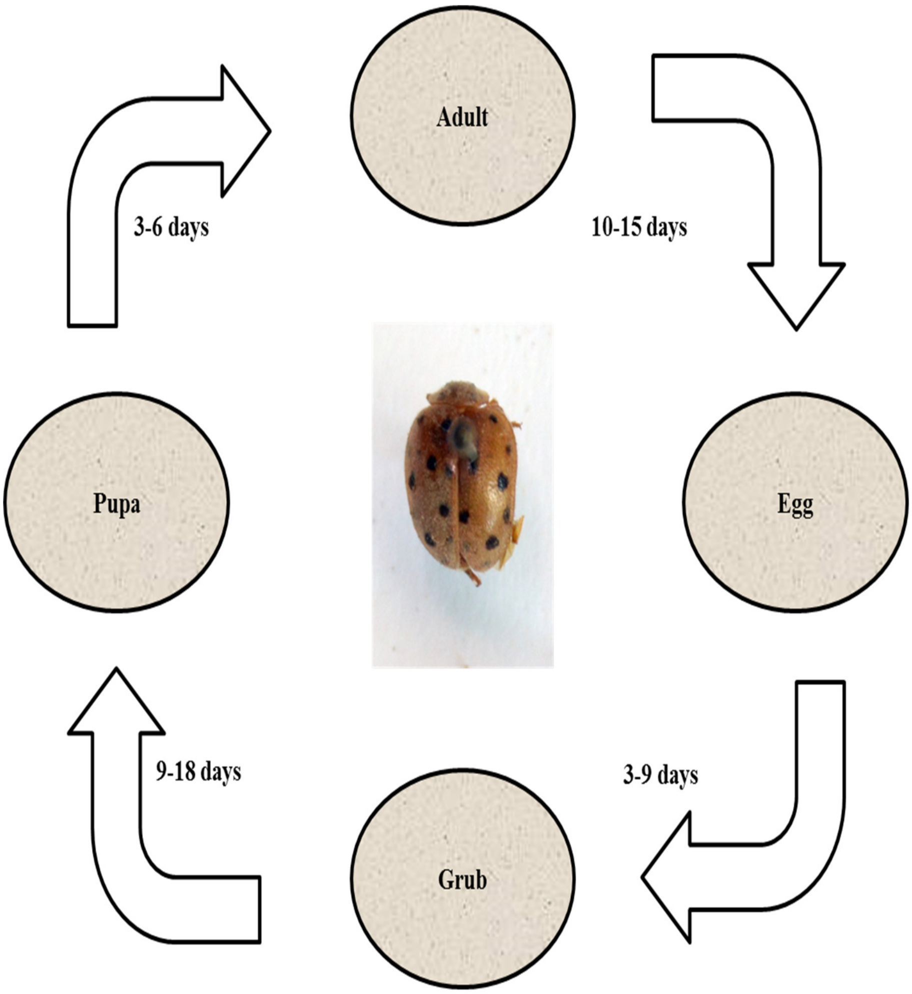

Fig. 6.21 Life cycle of Hadda beetle (*H. vigintioctopunctata* F.)

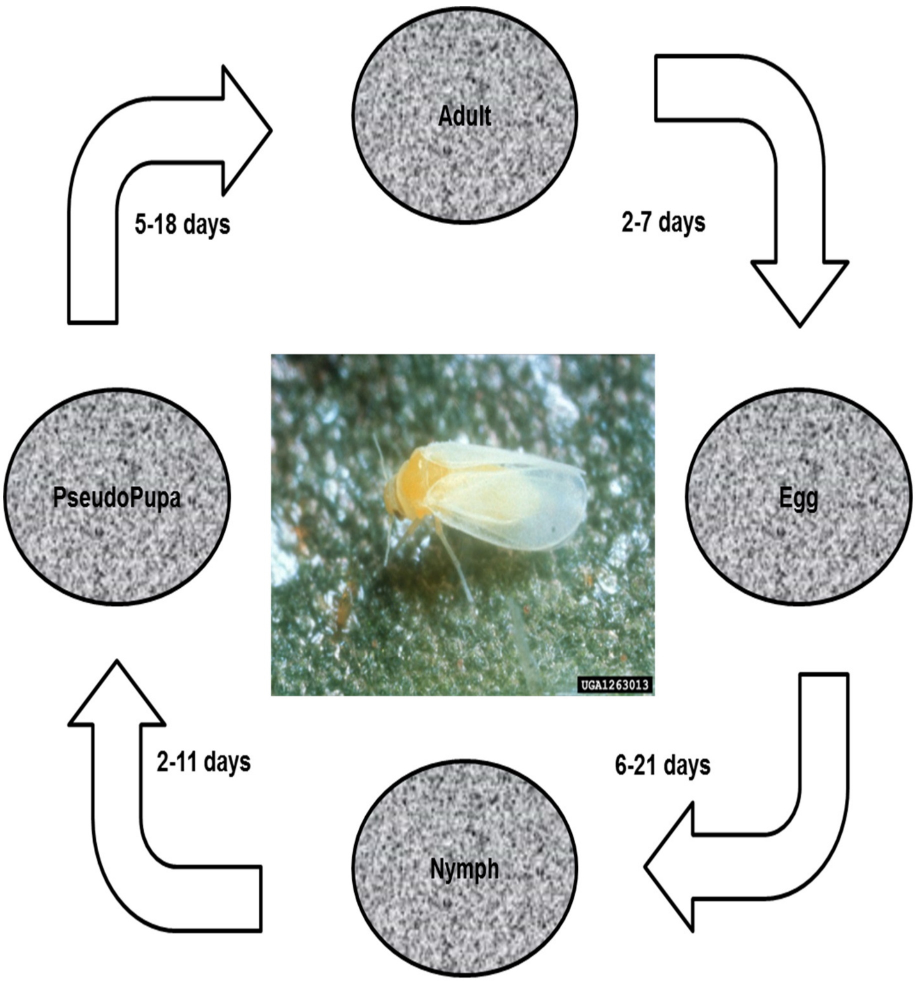

Fig. 6.22 Life cycle of Whitefly (*Bemisia tabaci* G.)

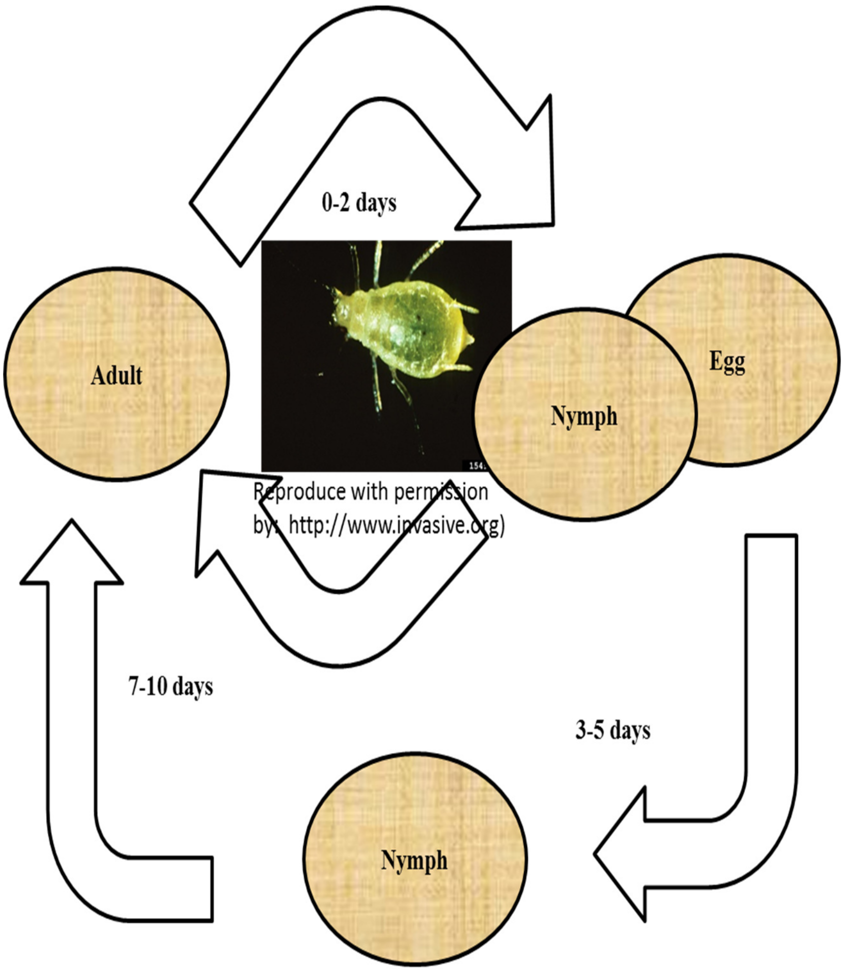

Fig. 6.23 Life cycle of Aphid (*Aphis gossypii* G.)

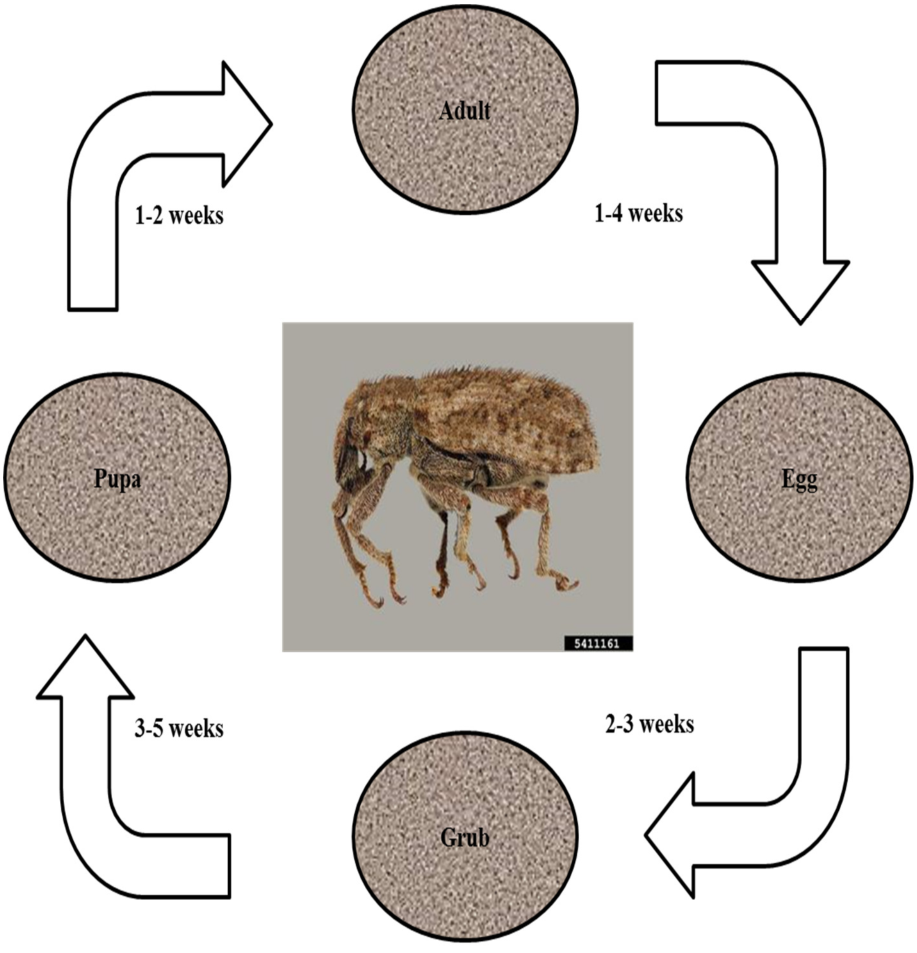

Fig. 6.24 Life cycle of vegetable weevil (*Listroderes constirostris obliquus* K.)

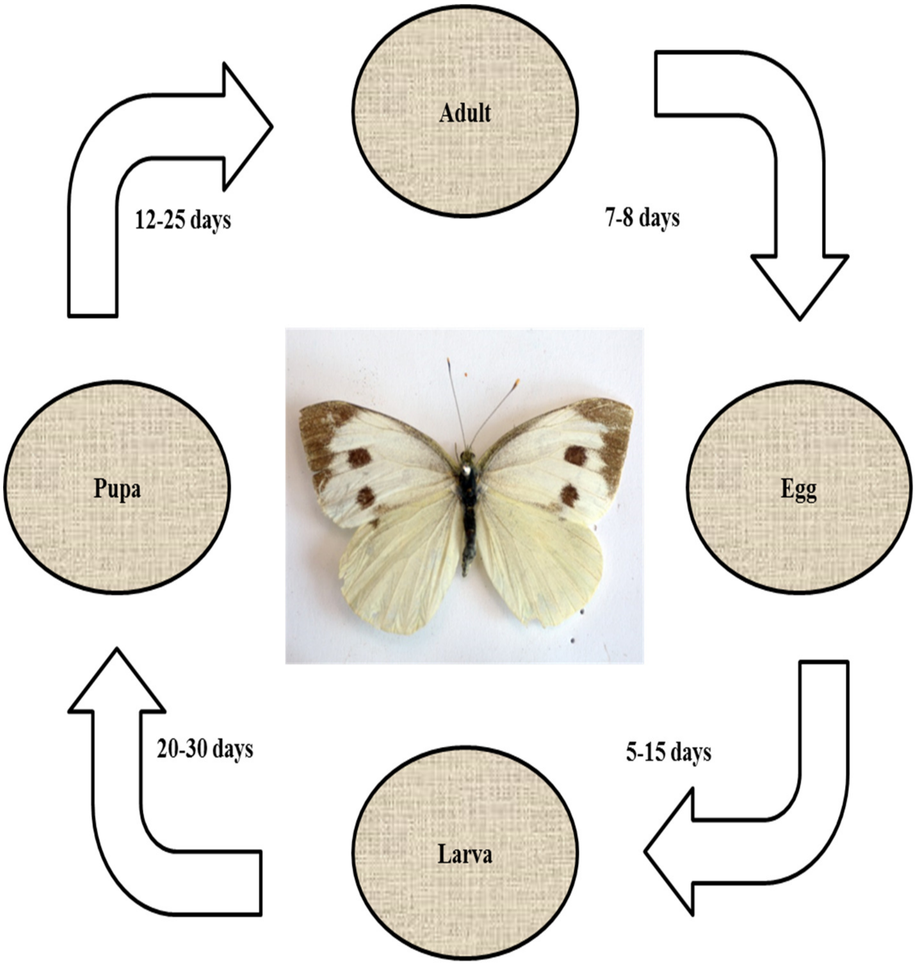

Fig. 6.25 Life cycle of cabbage butterfly (*Pieris brassicae* L.)

Table 1: Classification of vegetable crops

Class I: Annual Vegetables

Sub-Class I: Crops grown for subterranean parts. Groupe 1: Root Crops

Sr.	Common name	Botanical Name	Order	Family
1	Beet	*Beta vulgaris* L.	Caryophyllales	Amaranthaceae
2	Carrot	*Daucus carota* L.	Apiales	Apiaceae
3	Parsnip	*Pastiuaca sativa* L.	Apiales	Apiaceae
4	Radish	*Baphamis sativus* L.	Brassicales	Brassicaceae
5	Salsify	*Tragopogon porrifolius* L.	Asterales	Asteraceae
6	Scorzonera	*Scorzonera hispaniea* L.	Asterales	Asteraceae
7	Turnip	*Brassica rapa* L.	Brassicales	Brassicales
8	Horse-radish	*Cochlearia armoracia* L.	Brassicales	Brassicaceae
Groupe 2: Tuber Crops				
1	Potato	*Solanum tuberosum* L.	Solanales	Solanaceae
2	Sweet Potato	*Solanum tuberosum* L.	Solanales	Convolvulaceae
Groupe 3: Bulb Crops				
1	Onion	*Allium cepa*, *A. jistulosum* L.	Asparagales	Amaryllidaceae
2	Leek	*A. porrum* L.	Asparagales	Amaryllidaceae
3	Garlic	*A. sativum* L.	Asparagales	Amaryllidaceae
4	Cive	*A. selia-noprasum* L.	Asparagales	Amaryllidaceae
5	Shallot	*A. ascalonicum* L.	Asparagales	Amaryllidaceae
Sub-Class II. Crops grown for foliage parts. Groupe 4: Cole Crops				
1	Kale and Borecole	*Brassica oleracea* L.	Brassicales	Brassicaceae
2	Brussels prouts	*B. oleracea* L.	Brassicales	Brassicaceae
3	Cabbage	*B. oleracea* L.	Brassicales	Brassicaceae
4	Cauliflower and Broccoli	*B. oleracea* L.	Brassicales	Brassicaceae
5	Kohlrabi	*B. oleracea* L.	Brassicales	Brassicaceae
Group 5: Pot-herb Crops (used for "greens")				
1	Spinach	*Spinacea oleracea* L.	Caryophyllales	Amaranthaceae
2	Chard and Beet	*Beta vulgaris* L.	Caryophyllales	Amaranthaceae

Sr.	Common name	Botanical Name	Order	Family
3	Orach	*Atriplex hortensis* L.	Caryophyllales	Amaranthaceae
4	Purslane	*Portulaca oleracea* L.	Caryophyllales	Portulacaceae
5	Dandelion	*Taraxacum officinale* L.	Asterales	Asteraceae
6	Mustard	*Brassica species* L.	Brassicales	Brassicaceae
Group 6: Salad Crops				
1	Lettuce	*Lactuca saliva* L.	Asterales	Asteraceae
2	Endive	*Cichorium endivia* L.	Asterales	Asteraceae
3	Celery	*Apium graveolens* L.	Apiales	Apiaceae
4	Parsley	*Carum petroselinum* L.	Apiales	Apiaceae
5	Cress	*Lepidium sativum* L.	Brassicales	Brassicaceae
6	Upland or Winter Cress	*Barharea vidgaris* L.	Brassicales	Brassicaceae
7	Water Cress	*Nasturtium officiuule* L.	Brassicales	Brassicaceae
Sub-Class III. Crops grown for fruit or seed parts. Group 7: Pulse crops				
1	Bean	*Phaseolus vulgaris* L.	Fabales	Fabaceae
2	Pea	*Pisum sativum* L.	Fabales	Fabaceae
Group 8: Solanaceous crops				
1	Tomato	*Lycopersicum escidentum* L.	Solanales	Solanaceae
2	Egg plant	*Solanum melongena* L.	Solanales	Solanaceae
3	Pepper	*Capsicum annuum* L.	Solanales	Solanaceae
4	Physalis or Husk Tomato	*Physalis peruviana* L.	Solanales	Solanaceae
Group 9: Cucurbits or vine crops				
1	Cucumber	*Cueumis sattvus* L.	Cucurbitales	Cucurbitaceae
2	Melon	*C. melo* L.	Cucurbitales	Cucurbitaceae
3	Gherkin	*C. angaria* L.		
4	Watermelon.	*Citrus vulgaris* L.	Cucurbitales	Cucurbitaceae
5	Luffa	*L. acutangula* L.	Cucurbitales	Cucurbitaceae
6	Zit-Kwa, or Wax Gourd	*Benincasa cerifera* L.	Cucurbitales	Cucurbitaceae
7	Pumpkin	*Cucurbita pepo* L.	Cucurbitales	Cucurbitaceae
8	Squash	*Cucurbita* L.	Cucurbitales	Cucurbitaceae

Sr.	Common name	Botanical Name	Order	Family
Group 10: Corn, Okra, Martynia				
1	Sweet corn	*Zea mays* L.	Poales	Poaceae
2	Okra	*Hibiscus esciilentus* L.	Malvales	Malvaceae
3	Martynia	*Mariynia proboscidiu* L.	Lamiales	Martyniaceae
Group 11: Condimental and Sweet heres				
Group 12: Mushroom. (Culturally and otherwise the mushroom is so unlike other garden vegetables that it demands special and separate treatment. It is not a vegetable-gardening subject, although usually so classed.)				
Class II. Perennial Vegetables				
1	Asparagus	*Asparagus officitialis* L.	Asparagales	Asparagaceae
2	Ehubarb	*Rheum rhaponticum* L.	Caryophyllales	Polygonaceae
3	Docks	*Rumex patientia* L.	Caryophyllales	Polygonaceae
4	Sorrel	*Rumex*	Caryophyllales	Polygonaceae
5	Artichoke, Globe	*Cynara scohnmus* L.	Asterales	Asteraceae
6	Artichoke, Jerusalem	*Hejianthus tuberosus* L.	Asterales	Asteraceae
7	Sea Kale	*Crambe viaritima* L.	Brassicales	Brassicaceae

Table 2: Major insect pests of different vegetable crops.

Sr.	Common Name	Technical Name	Family	Order
1	Brinjal Lace-wing Bug	*Urentius serais* Distant	Tingidae	Homoptera
2	Hadda beetle	*Epilachna vigintioctopunctata* Fabricius	Coccinellidae	Coleoptera
3	Red Pumpkin Beetle	*Aulacophora foveicollis* Lucas	Chrysomelidae	Coleoptera
4	Green Sting Bug	*Acrosternum hilare* Say	Pentatomidae	Lepidoptera
5	Cabbage Butterfly	*Pieris brassicae* Linnaeus	Pieridae	Lepidoptera
6	Brinjal Fruit Borer	*Leucinodes orbonalis* Guenée	Pyralidae	Lepidoptera
7	Melon Fruit Fly	*Bactrocera cucurbitae* Coquillett	Tephritidae	Diptera
8	Brinjal Stem Borer	*Euzophera perticella* Ragonot	Pyralidae	Lepidoptera

Sr.	Common Name	Technical Name	Family	Order
9	Cabbage Semi-looper	*Chrysodeixis eriosoma* Doubleday	Noctuidae	Lepidoptera
10	Potato Tuber Moth	*Phthorimaea operculella* Zeller	Gelechiidae	Lepidoptera
11	Mustard Sawfly	*Athalia proxima* Klug	Tenthredinidae	Hymenoptera
12	Diamond Back Moth	*Plutella xylostella* Linnaeus	Plutellidae	Lepidoptera
13	Painted Bug	*Bagrada hilaris* Burmeister	Pentatomidae	Hemiptera
14	Green/Potato Bug	*Nezara viridula* Linnaeus	Pentatomidae	Hemiptera
15	Onion Thrips	*Thrips tabaci* Linnaeus	Thripidae	Thysanoptera
16	Tobacco Caterpillar	*Spodoptera litura* Fabricius	Noctuidae	Lepidoptera
17	Tomato Fruit Borer	*Helicoverpa armigera* Hübner	Noctuidae	Lepidoptera

Sources: (Capinera 2001; Reddy and Zehr 2004; Grzywacz, Rossbach et al. 2010)

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Chapter 7

Insect Pathogens as Potential Biocontrol Agents

Waqas Wakil and Yong Jung Kwon[†]

Abstract

Insect pest threat is a major factor that causes diseases in human beings and disrupts crop productivity in agro ecosystems. The middle era of the last century is the keynote witness of chemical insecticides augmentation for the management of insect pests and their backlashes. These chemical insecticides are the silent killers, and are responsible for the development of resistance in pests, environmental persistence and toxicity. A striking substitute to chemical insecticides is the use of Microbial Biocontrol Agents (MBCAs). These entomopathogens are natural enemies of insect pests devastating their populations with no hazardous effects on environment and human health. The MBCAs are not only good alternatives to hazardous chemical pesticides but their immense selectivity by infecting very narrow range of host pests is the key features of their effective utility.

Keywords: Entomopathogenic fungi, bacteria, viruses, nematodes, biological control

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7.1. Introduction

The science of invertebrate pathology provides the scientific fundamentals of microbial control. Insects and microorganisms have ancient and old complex relationship well described by the insects conserved in amber before 15 to 20 million years ago. The collection of several insect cadavers dressed with entomopathogens like neucleopolyhedrovirus (NPV), nematode and trypanosomes is reported (Poinar and Poinar 2005). It has been an old profession, however, its roots can be traced to ancient history from the Aristotle's times (2700 BC), who observed the diseased silk worm with whitish growth on the dead larvae of silk worm during 335 BC in China. It was not until the work of Agostino Bassi (1773-1856) an Italian Lawyer and Scientist, reported the fungus *Beauveria bassiana* (Balsamo-Crivelli) Vuillemin on the larvae with a whitish sooty growth. Thus enunciating the germ theory of disease and named "calcinaccio" disease because the dead larvae exhibit whitish calcium powder like coverings (Steinhaus 1956, 1975).

Agostino Bassi observed that the causal agent of the disease is "vegetable parasite" - a fungus now called *B. bassiana* which may be transferred through inoculation, contact or by the ingestion of the leaves by the caterpillar. This was the first research of Bassi which confirmed that microorganisms can cause disease and also it was the important contribution towards disproving the idea of spontaneous generation. Calcinaccio disease was found plaguing the silk industry first time in Italy (1805) and then in France (1841). Bassi conducted the scientific study on Calcinaccio disease in 1807. After a long term and comprehensive observation, during the year 1835 Bassi confirmed that this disease causing entity is a living organism which may produce whitish growth on the dead larvae. He was honored with rescuing the precious and economically important industry of silk by providing his valuable suggestions for the use of separating the rows of caterpillars feeding on the mulberry leaves, disinfection process, destroying dead cadavers, keeping the rearing room clean and infection free. His findings were translated and distributed throughout the Europe which greatly helps Louis Pasteur (1822-1895) to study the cause and potential cure of the disease in Europe (Porter 1973). In the same year, famous Italian naturalist Giuseppe Gabriel Balsamo-Crivelli studied and named the fungus, *Botrytis bassiana*, *Beauveria bassiana* (Balsamo-Crivelli) Vuillemin in the honor of Bassi (Steinhaus 1949; Müller-Kögler 1965; Rehner 2005). The species *B. bassiana* came into existence when in 1911 Beauverie studied the fungus again and Vuillemin created the new genus *Beauveria* in honor of Beauverie in 1912, since then the species *B. bassiana* became the type.

In 1865, French silk industry was badly devastated and Louis Pasteur was asked to identify the disease. He was not reluctant to accept the offer as he was not fully aware about silk worms, although he was persuaded by his teacher and friend Senator Jean-Baptist Dumas to move and consult to famous entomologist Jean Henri Fabre (1823-1915) in Alés Village in the south of France. After the efforts of several years he came to the result that two silk worm diseases "pébrine" and "flacherie" (thought to be caused by bacterium) are responsible for the decline of silk industry. He proposed that pébrine is characterized by tiny black spots on the surface of dead larvae of silk worm caused by the microorganism *Nosema bombycis*, previously described by

Nägeli (1857). For the potential elimination of the disease, he proposed that careful handling, segregating healthy from diseased larvae and well maintained sanitation may be helpful in disease prevention (Debré 1998).

During the study it was found that disease can be transmitted by contaminated food, contact with the infected caterpillar and even from mother to the offspring. This is the first study demonstrating the vertical transmission of the disease (Pasteur 1874). He published his findings in two series to make aware the people about silk worm disease and its protection (Pasteur 1874). This work laid the foundation of advance sericulture in Japan dealing with the molecular and biochemical biology of the silk worm. The scientists like, Agostino Bassi, Louis Pasteur and Elie Metchnikoff, the 19^{th} century pioneers also proposed that these microorganisms can be a good solution for controlling economically important insect pests (Steinhaus 1956, 1975). Number of developments in invertebrate pathology took place in the first half and late of the 19^{th} century, it wasn't until the discovery of *Bacillus thuringiensis* (*Bt*) Berliner, when practical and commercial use of microbial control began on a large scale (Lacey and Goettel 1995).

In 1879, Metchnikoff discovered the diseased larvae of wheat cockchafer and later on *Cleonus punctiventris* Schonherr near Odessa (Ukraine). He named this fungus as green muscardine fungus. The genus *Metarhizium* was first described by Sorokin (1883). For this fungus, he first proposed the name *Entomophthora anisopliae* Metchnikoff and later renamed as *Isaria destructor* Metchnikoff. The history of the description, discovery, the scientific research and on the use of fungus in biological control is described in detail by Steinhaus (1949) and Müller-Kögler (1965). In the start of 20^{th} century *B. thuringiensis* was first isolated, from infected silk worm larvae by a Japanese bacteriologist (Ishiwata 1901) and subsequently in 1911 German biologist Berliner re-discovered the disease. He isolated the bacterium from infected larvae of Mediterranean flour moth, collected from a mill in Thuringe Province (Berliner 1915), so named this bacterium *B. thuringiensis.* Because of high and knock down mortality effects with small amount of *B. thuringiensis* preparations, the agronomist get aware about the insecticidal properties of this bacterium. The first *B. thuringiensis* based commercial formulation "Sporéine" was developed in France in 1938, but the 1^{st} well documented record of commercial procedure for producing *Bt*-based product dates from 1959 by the "Bactospéine" under the 1^{st} French patent as a bio-pesticide formulation. Since after, a vast array of microorganisms like fungi, bacteria, viruses and protozoans has been identified as potential biocontrol agent against insect pests (Riba and Silvy 1989). So far, even though more than 100 species of entomopathogenic bacteria have been identified, only few *Bacillus* species have met with commercial success, *B. thuringiensis* in particular (Starnes et al. 1993).

Today a variety of microbes are used for the control of arthropod pests of field crops, glasshouse, row crops, ornamentals, stored products, orchards, range, turf and lawn, forestry and for the abatement of insect vectors and pests of medical and veterinary importance (Tanada and Kaya 1993; Lacey and Kaya 2007). Entomopathogenic microbes used as a microbial control include viruses, bacteria, protozoa, fungi, and nematodes. Considering the adverse effects of conventional chemical insecticides, environmental and public health issues in tropical countries, these biopesticides which exert only a minor impact on the environment have occupied the stable position, although modest in the insecticide market. The share of biopesticide in crop protection market is about 600 million US$ which accounts for only 2% of the total pesticides, with about 90% of all bio-pesticide sales involving products based on *B. thuringiensis*.

The comparison of microbial pesticides with chemical pesticides is usually exclusive from the view point of their cost effectiveness. These microbial insecticides offer unique advantages when there are environmental and human safety concerns along with the increasing need of enriched biodiversity in an ecosystem and increased activity of natural enemies (Shahid et al. 2012). Furthermore, easy application method, production on artificial medium and long term storage are further distinct features of these insecticides over other insect control tactics.

7.2. Entomopathogenic fungi

The ancient surveillance history and research of mycopathogens invading insect pests is long standing thousands of years. Before the invention of microscopes fungi can be seen with naked eye and this observation helped in invention of invertebrate pathology as a modern study. Fungi are categorized in a number of taxa that exhibit greater diversity in properties, requirements and found in all arthropod habitats. As a result, great attention was diverted in using fungi as microbial control of insect pests. The fungi are heterotrophic, eukaryotic, absorptive individuals which may develop in different patterns like diffuse, branched, or tubular body that can reproduce sexually as well as asexually (Kendrick 2000).

The primitive studies regarding entomopathogenic fungi (EPFs) were conducted during start of 18th century with an aim to develop control strategies for managing muscardine disease of silk worm (Steinhaus 1975). Bassi (1835 as cited by Steinhaus 1975) proposed the germ theory using silkworm and invading fungus, later this was named as *B. bassiana* in the honor of Bassi. His studies on silkworm disease assisted him to introduce the fungal biocontrol agents for the control of insect vector that elicit disease in human beings. The silkworm diseases provided gross root foundations for the control of insect pests by employing entomopathogens. Nevertheless, the major efforts were attempted in deploying EPFs for the control of insect pests carried out during 1950's when chemical insecticides were invented. There are many fungal based products commercially available worldwide now-a-days (Shah and Goettel 1999; Copping 2001).

7.2.1. History

EPFs have a long primordial historic recognition; their illustrated descriptions can be seen centuries back, infection of *B. bassiana* and *Cordyceps* sp. (L.) Fr. to silk worm described in ancient Japanese paintings infections of insects date from the 19th century (Samson et al. 1988). As a vocation, invertebrate pathology is an organized discipline. Historic stories can be drawn from the solution of silk worm and honey bee diseases prevention from entomopathogens (Steinhaus 1956, 1975). Very first reports of managing insect pests in insect pathology with entomopathogenic fungi were proposed by the legend pioneers like Louis Pasteur, Elie Metchnikoff and Agostino Bassi (Steinhaus 1975).

Currently numerous entomopathogens are deploying for managing insect pests in lawn and turf, orchards, glasshouse, ornamentals, row crops, forestry, range lands, stored products, pest and insect vectors of medical and veterinary importance (Tanada and Kaya 1993; Lacey and Kaya 2007).

7.2.2. Classification

Among different fungal divisions, entomopathogenic fungi are found in the Ascomycota, Zygomycota and Deuteromycota (Samson et al. 1988), Chytridiomycota and Oomycota (previously classified within Fungi). Many of the genera of entomopathogenic fungi currently under research belong either to the class Hyphomycetes in the Deuteromycota or to the class Entomophthorales in the Zygomycota. The general classification of entomopathogenic fungi is given in Table 1.

Table 1 Classification of entomopathogenic fungi

Division	Class	Order	Family	Genus
Zygomycota	Zygomycetes	Entomophthorales	Entomophthoraceae	Entomophaga
				Entomophthora
				Erynia
				Eryniopsis
				Furia
				Massospora
				Strongwellsea
				Pandora
				Tarichium
				Zoophthora
			Neozygitaceae	Neozygites
Ascomycota	Sordariomycetes	Hypocreales	Clavicipitaceae	Beauveriaa
				Cordyceps
				Cordycepioideus
				Lecanicilliuma
				Metarhiziuma
				Nomuraea

Source: (Roy et al. 2006)

7.2.3. Host range

Fungal infections to the most insect orders with all life stages have been observed, while infection to the immatures of holometabolous insects have been reported more commonly (Tanada and Kaya 1993). The host range may differ significantly among different species of EPFs and even among different strains of the same single species. For obligate pathogens, specifically restricted to a narrow host range and complicated life cycles associated to their insect host like *Strongwellsea castrans* Batko and Weiser, restricted to flies like anthomyiid (Eilenberg and Michelsen 1999) and entomophthorales, *Massospora* sp. are restricted to a single genus belonging to cicadas (Soper 1974). In contrast, deuteromycetes, particularly *B. bassiana*, have wide host range including numerous genera of insects (McCoy et al. 1988). It must be kept under consideration that description of host range to some extent mainly relies on laboratory studies which do not reflect the true picture in nature. Some factors like insect host, fungal biology and ecology may be responsible for reducing infection in insect host. It is important to mention that fungi are capable of infecting several other arthropods, insects and the species which are not pests of cultivated crops (*Gibellula* species infect spiders and *Cordyceps* sp. and *Erynia* infect ants) (Shah and Pell 2003).

7.2.4. Mode of infection

The fungal infection to insect host is a complex process, involving chemical and physical procedures starting from spore attachment to the host death. Following steps are undertaken during infection process: (1) attachment of the spore to the host cuticle, (2) germination of fungal spore, (3) penetration into the host cuticle, (4) overcoming the immune defense mechanism, (5) formation and proliferation of hyphal bodies into the haemocoel, (6) saprophytic outgrowth from the dead host, production and dissemination of new conidia. For the successful attachment, mainly hydrophobicity of the spore and cuticular surface play significant role.

Furthermore, the germination and successful infection is affected by a number of factors e.g., susceptible host stage, humidity, optimal temperature and cuticular lipids, such as aldehydes, ketones, short-chain fatty acids, wax, esters and alcohols which may exhibit antimicrobial activity. Generally, fungal spores breach through the non-sclerotised areas of the cuticle such as joints, between segments or the mouthparts. The conidial germination starts after 10 h of attachment and may complete by 20 h at 20-25^{o}C. Before infection process, germ tube produce appressorium or penetration pegs which is accompanied by mechanical and chemical processes by the production of several enzymes (proteases, chitinases and lipases etc.) (Ortiz-Urquiza and Keyhani 2013).

The enzymes responsible for pathogenesis are generally grouped as chitinases, proteases, peptidases, and lipases as follows:

7.2.4.1. Chitinases

The chitin is a major constituent of the insect cuticle, therefore, endo- and exo-chitanses are important enzymes for the breakdown of N-acetylglucosamine polymer of insect cuticle into monomers and a key factor determining the fungal virulence (Khachatourians 1991). Endochitinases, N-acetyl-β-D-glucosaminidases and chitinolytic enzymes from *B. bassiana*, *M. anisopliae* (Metchnikoff) Sorokin and *Metarhizium flavovirid* Gams and Roszypal were presented in broth culture nourished with insect cuticles.

7.2.4.2. Proteases and peptidases

Chitin and protein are the main constituents of insect cuticle; hence proteases and peptidases of EPFs is considered key degrading enzymes of insect cuticle, saprophytic growth, initiation of prophenol oxidase in insect haemolymph, furthermore they are also responsible for virulence in EPFs. Some genes of overlapping response with a unique expiration pattern were observed when encountered with the cuticle of *Lymantria dispar* (Linnaeus), *Blaberus giganteus* (Linnaeus) and *Popilla japonica* Newman using cDNA counted gene expression responses to the cuticles of number of host insects and constructed microarrays from expressed sequence tags, clone of 837 genes (Freimoser et al. 2005).

7.2.4.3. Lipases

The epicuticle of the insects is chiefly composed of non-polar lipids which play an important role in chemical signaling between insect host and EPFs (Blomquist and Vogt 2003). It keeps cuticular outer surface dry which aids to avoid the penetration of chemicals and insecticides (Blomquist et al. 1987; Juárez 1994). They are chemically stable with high molecular mass, mainly due to the presence of specific physicochemical characteristics, like number of carbons, length of the chain and the kind and position of double bond and the functional groups. The long chain HC, free fatty acids, fatty alcohols and wax esters are ample components of the insect epicuticle. It also contains fats, waxy layers and lipoproteins which act as a barrier to the action of lipoxygenases and lipases of eontomopathogenic fungus. Among these compounds some have anti-fungal activities (Khachatourians 1996) while some other possess saturated fatty acids which can inhibit the fungal growth.

7.2.5. Toxins

The biochemical properties and structure of some major fungal metabolites have been investigated in detail (Vey et al. 2001), but very few studies have been conducted regarding the metabolite production under field conditions (Bandani et al. 2000; Strasser et al. 2000). One major problem to fungal toxins is that one type of fungi can produce variety of bioactive metabolites and risk assessment to these entire compounds would be enormous. Furthermore, fate of their toxins is little known in the environment, which would be the key question for their registration.

7.2.5.1. Destruxins

Destruxins are moderately dissimilar compounds which occur as isomers. Basically destruxins contain 5 amino acids and α-hydroxy acid which may be found in many different forms. So far 28 different but structurally similar destruxins have been isolated from different EPFs mostly were discovered from *M. anisopliae* isolates (Vey et al. 2001). Insects exhibit varying susceptibility levels to destruxins and lepidopterans have been reported as the most susceptible amongst the all studied insect orders (Samuels et al. 1988; Kershaw et al. 1999). The toxicosis symptoms also vary among insect pests - the most peculiar symptom is an immediate tetanus; which at low concentrations develops for up to three minutes period, while brief or no paralysis is depicted at high dose rates (Abalis 1981; Samuels et al. 1988).

7.2.5.2. Oosporein

Oosporein is produced mainly from the soil inhibiting fungi like *Beauveria* spp. which contain red colored di-benzoquinone (Eyal et al. 1994). It reacts with amino acids and proteins through redox reaction by altering the SH-groups and results malfunctioning in enzymes (Wilson 1971). Like bassianin and tenellin, oosporein also inhibit the activity of erythrocyte membrane ATPase which is directly proportional to the dose rate of oosporein. Upto 50% activity can be ceased at 200g/ml. All these pigments greatly influenced Ca^{2+}-ATPases compared to the activity of Na^{+}/K^{+}-ATPase. Antibiotic effect of oosporein against gram-positive bacteria has also been observed with no or little effect on gram negative bacteria (Taniguchi et al. 1984; Wainwright et al. 1986).

7.2.5.3. Beauvericin and beauveriolide

Beauvericin is also an important toxin isolated from *Beauveria*, *Paecilomyces* sp. Samson, the plant pathogenic fungi *Polyporus fumosoroseus* and *Fusarium* sp. (Gupta et al. 1991; Plattner and Nelson 1994). Gupta et al. (1995) described two different forms of these toxicants Beauvericin A and B forms K^{+} and Na^{+} complexes, which increase the membranes permeability (Ovchinnikov et al. 1971). It also exhibits antibiotic activity against a number of bacteria like, *Escherichia coli* Migula, *Mycobacterium phlei* Lehmann and Neumann, *Bacillus subtilis* Ehrenberg, *Sarcinea lutea*, *Streptococcus faecalis* and *Staphylococcus aureus* Rosenbach (Ovchinnikov et al. 1971).

7.2.5.4. Bassianolide

Another toxin cyclo-octadepsipeptide also called bassianolide is secreted by *B. bassiana* (Suzuki *et al.* 1977). Bassianolide is also an ionophore which exhibits different reactions with different hosts (Kanaoka et al. 1978). Very little is known about the toxic nature of bassianolide against plants and animals, the synergistic interaction with the structurally associated mycotoxin moniliformin may be possible.

7.2.5.5. Beauveriolide

Beauveriolide were isolated from *Beauveria* spp. which is structurally related to bassianolide and beauvericin (Namatame et al. 1999). The toxic effect of beauveriolid towards plants and animals is still unknown except beauveriolide I (Mochizuki et al. 1993). Over all these cyclodepsipeptides may still have an unreported health hazard effects is common. Except the above mentioned metabolites these *B. bassiana* also produce bassianin, tenellin and two non-peptide toxins isolated from *Beauveria* spp. which aid in inhibiting the erythrocyte membrane ATPases (Jeffs and Khachatourians 1997).

7.3. Bacteria

Existence of bacteria is as old as the history of life on earth. Evidence of rocked bacterial fossils date back to Devonian period (416-359.2 million years ago) and considerable signs depict their presence from Precambrian time, about 3.5 billion years ago. The fossils found in north-west Australia's Pilbara region are thought to be nearly 3.5 billion years old and considered the oldest ones on earth planet. In Proterozoic Eon (about 1.5 billion years ago), when the activity of cyanobacteria resulted in oxygen production, bacteria became widespread (*Anonymous 2013)*. The gradual evolution of the bacteria made them able to survive under wide range of environment with several descendent forms. As a result of this, today an uncountable and immeasurable diversity in morphology, physiology and taxonomy of bacteria prevails. Bacteria have been found living very close to other living organisms particularly human beings. Both beneficial and harmful forms of bacteria have been thriving in various climates like soil, water, air and hot water springs etc.

Within the preview of Prokaryotes, bacteria are the microorganisms that lack the nuclear membrane which separates genetic material from cytoplasmic contents and other membrane bounded organelles. Bacteria surround us all around and thus, can be isolated from any environment and hence their enriched flora can be given the name of metabolic strategy which they use to earn energy such as *phototrophs* (gain energy from sunlight), *lytotrophs* (obtain energy form inorganic material) and *organotrophs* (receive energy from organic material). The variation in their size is from one to few microns, and depending upon the morphologies, they can be grouped as *cocci* (spherical), *bacilli* (rod shaped) and *spirochetes* (spiral shaped). Propagation in bacteria is carried out through binary fission, a mode of asexual reproduction in which daughter cells is produced from mother cell as clonal copies (Jurat-Fuentes and Jackson 2012).

7.3.1. Classification

The recognized factor for classifying bacteria involves the sequence of 16S ribosomal RNA. Two important groups of bacteria are *Eubacteria* (true bacteria) and *Archaea* containing bacteria having similar features of DNA replication, transcription and translation as exhibited by eukaryotes. Three major divisions within Eubacteria are primarily based on the presence or structure of cell wall: *Gracilicutes* Gibbons and Murray (gram negative typed cell wall bacteria), *Firmicutes* Gibbons and Murray (gram positive typed cell wall bacteria) and *Tenericutes* Murray (Eubacteria which are devoid of cell wall). Most recent classification within Eubacteria mostly relies on the use of polyphasic taxonomy that includes analysis of nucleotide sequence of RNA (16S rDNA), DNA-DNA hybridization, genotypic, phenotypic and phylogenetic aspects (Brenner et al. 2005). Entomopathogenic bacteria; greatly concerned with entomological studies are grouped in Eubacteria.

The cell wall of bacteria greatly serves the purpose to classify, support molecules and organelles. In gram-positive bacteria, the cell wall is formed of cross-linked peptidoglycan. On the other hand, cell wall in gram-negative bacteria is formed of rather complex thin layer of peptidoglycan, lipoproteins and an outer polysaccharide membrane. Gram-negative bacteria are distinguished from gram-positive bacteria by lacking the ability to retain crystal violet dyes. Gram-positive are endospore forming, rod and cocci shaped bacteria often undergoing sporulation. Gram-negative bacteria on the other hand appear to be in rod or cocciform. They are much more diverse in their distribution, also can be isolated from diseased and dead insect specimens (Jurat-Fuentes and Jackson 2012).

7.3.2. Entomopathogenic bacteria

7.3.2.1. History

Confirmatory evidences of using entomopathogens for the control of insect pests are not known, however, human interest in exploiting microbes particularly bacteria rose to its extreme after the discovery and the commercial availability of microscope in late 19th and early 20th century. Scientific efforts for the survival of famous Japanese silk industry against sudden death of caterpillars proved fruitful resulting in the discovery of spore forming bacterium *Bacillus sotto* by Sigetane Ishiwata (1868-1941) (Aizawa 2001). This discovery lead to the world's first ever demonstration of toxin when many other scientists including Aoki and Chigasaki (1915) and Mitani and Watari (1916) found enhanced lethal action of bacterial culture on silk worms when it was dissolved in alkaline solution (Aizawa 2001). Doors of discoveries were opened for man and a German scientist Ernst Berliner in 1909 isolated a bacterium named by him as *B. thuringiensis* that killed Mediterranean flour moth, *Ephestia kuehniella* Zeller (Lepidoptera: Pyralidae).

7.3.2.2. Mode of infection

The ingestion of *B. thuringiensis* compounds by insects follows the route of mid gut to expose it to alkaline environment of gut (pH >9.5). Here the higher pH of the gut solublizes the inactive, otherwise insoluble proteins resulting in the release of crystal proteins that produces δ-endotoxins. This proteolytic activation of δ-endotoxins offers an extraordinary insecticidal activity to insects and this activated toxin readily gets bound to specific receptors present at apical brush border of the midgut microvillae in target insects (Hofmann et al. 1988). The toxic action of proteins is attributed to N-terminal half consisting of seven anti-parallels α-helices. These α-helices offers potential gradient by penetrating the membrane and forming an ion channel in apical brush border membrane allowing rapid flux of ions. Loss of integrity of insect's gut is the outcome of *B. thuringiensis* activity causes starvation and septicemia which leads to the death of insects (Kumar et al. 2013).

The penetration of α-helices in the apical brush border membrane forms an ion channel (Knowles and Dow, 1993). As a result, rapid flux of ions takes place because of toxin-induced pores formation (Wolfersberger 1989). Consequently the gut integrity gets lost that resultant starvation and/or septicemia leads to insect death.

A wide array of *B. thuringiensis* products formulated for commercial uses have an extended spectrum of action effective to secure food crops, forest trees, stored grains and ornamentals (Meadows 1993). Contrary to hazards associated to chemical pesticides, *B. thuringiensis* formulation offers a wide range of benefits. Although it is highly virulent to target insects, yet it is harmless to non-target insects due to its specificity. In spite of decades of use in field, *B. thuringiensis* toxins are still reported as non-hazardous to animals, human beings and other non-target pests. All these characteristics render it highly suited to include IPM programs (Nester et al. 2002). Besides these benefits, *B. thuringiensis* formulations have some associated limitations (McGaughey and Whalon 1992). One of the limitations is its effectiveness against specific stage of insect especially immature stage. For this reason, an effective control of targeted insect requires repeated application. *B.*

thuringiensis products perform excellently against insect pests exposed to environment than insects concealed within plant parts or some other structures. But the expression of *B. thuringiensis* gene(s) using transgenic cultivars (Krattiger 1997) can come up with all such concerns.

7.3.3. Important entomopathogenic bacteria

7.3.3.1. Paenibacillus popilliae

Paenibacillus popilliae Dutky formerly known as *Bacillus popilliae* Dutky is a gram-positive, spore-forming bacterium which was initially isolated from infected Japanese beetle (*Popillia japonica* Newman) (Coleoptera: Scarabaeidae) larvae in the late 1930s and then named after the name of its first host. The spore forming capability of bacterium protects it from heat, cold, drying and other harsh environmental regimes.

Paenibacillus popilliae plays a major role in biologically managing scarabs, particularly Japanese beetle (Petterson et al. 1999). *Bacillus popilliae* has been reported from at least 29 scarabs, mostly from Melolonthinae and Rutelinae. *Paenibacillus popilliae causes milky spore disease in P. japonica* and it is the first pathogen registered as insect biological control in USA.

7.3.3.2. Brevibacillus laterosporus

Brevibacillus laterosporus Laubach is a gram-positive, rod-shaped, endospore-forming bacterium and is considered an important entomopathogenic and antimicrobial agent. It is morphologically distinguished by producing characteristic canoe-shaped parasporal body (CSPB) firmly attached at one end of the spore imparting it lateral position in the sporangium. Ubiquitous existence of this bacterium has enabled its isolation from various reservoirs particularly soils, insect bodies, fresh and sea water, leaf surfaces, compost, milk, honey, factory effluents, animal hide, wool and many other materials (Ruiu 2013). It was discovered by White (1912) during 20^{th} century associated with honey bees determined during an investigation on European foulbrood.

7.3.3.3. Bacillus subtilis

German botanist Ferdinand Cohn in 1877, while working on hay *Bacillus*, discovered two new forms of *Bacillus* strain named *Bacillus subtilis*; one of them was heat sensitive (without endospore) while other was heat tolerant (endospore). A significant genomic diversity in the bacterium has been publicized using genomics analysis based on microarray-based techniques. It is competent for growth in many environmental conditions and is often considered as soil dweller. Most common sources of its isolation are air, soil, water and decomposing plants. However in most of the cases, it is not found naturally in biologically active but occurs in spore forms. *Bacillus subtilis* is scientifically fabulous for its ability to produce a number of antibiotics especially bacitracin and iturin. It regulates the development of adult mosquitoes by inhibiting their growth (Ramathilaga et al. 2012).

7.3.3.4. Bacillus sphaericus

Bacillus sphaericus is a naturally occurring spore-forming gram positive bacterium that exhibits strong insecticidal properties. It possesses efficient larvicidal properties against mosquito by producing delta-endotoxins via sporulation that binds strongly to receptors in midgut epithelial lining of mosquito larvae. The bacterium has narrow spectrum and quite specific activity that sometimes decreases its demand for use in field. Enhanced time of lethal action against some mosquito species and recycling of toxin within dead mosquito sometimes works as limiting factors for its use. One of the advantages exhibits over *B. thuringiensis* var. *israelensis* is its longer persistence that provides long lasting control (Filha et al. 2008).

7.3.3.5. Wolbachia

Wolbachia are inherited from α-protobacteria, litreally the members of the order Rickettsiales; a varied group of intracellular bacteria that comprises species exhibiting parasitic, mutualistic and commensal associations with their hosts. With its pathogenic nature extended to arthropods and filarial nematodes, it is regarded as the most common endosymbiotic bacterial species on the globe. The only member contained with genus *Wolbachia* in family Anaplasmataceae and order Rickettsiales is *Wolbachia pipientis* Hertig; rest of species; *W. melophagi* Noller, Philip and *W. persica* Suitor and Weiss have been recently declared as unrelated (Dumler et al. 2001). An insight into the intracellular life study of the bacterium ensures its obligate nature of infection to hosts and it has been found successfully infesting about 66% of the insect species (Hilgenboecker et al. 2008). *Wolbachi*a being intracellular bacterium get vertically transmitted through egg. The outcome of this cellular transmission is the manipulation of reproduction by invading bacteria that mostly appears in the form of cytoplasmic incompatibility. One of the vital reasons behind the successful propagation of *Wolbachia* in arthropods is its inherent ability to take control of the host's reproductive cycle by providing nutrients and protecting host from other pathogens (Hosokawa et al. 2010).

The genera quite related to *Wolbachia*; *Anaplasma*, *Ehrlichia* and *Neorickettsia* during their life stages include an invertebrate 'vector' and mammalian 'host' and in some cases invertebrate associations in some species have also been found. But contrary to unlike members, *Wolbachia* not necessarily involves or infects vertebrates. One of the important reasons behind increased interest for *Wolbachia* is their immense diversity, interesting phenomena shown while infecting their hosts such as reproductive manipulation, and their possible exploitations for pest and disease vector control (Bourtzis 2008).

7.3.3.6. *Bacillus thuringiensis*

Bacillus thuringiensis (*Bt*) holds a prominent position among commercial chemical compounds important for agricultural insect pests. It is a naturally occurring spore forming, gram-positive bacterium. It has been found as a source and reservoir of several important insecticidal proteins like δ-endotoxins, vegetative insecticidal proteins (vip) and cytolytic proteins etc. Among these proteins, δ-endotoxins have a vital role in protecting number of important crops from various insect pests. *Bacillus thuringiensis* insecticides have proved their worth as a biopesticide to protect food crops, cash crops, ornamentals, forest trees and stored commodities (Meadows 1993).

For convenience, life cycle of *B. thuringiensis* can be divided into different phases; Phase-I: vegetative growth; Phase-II: transition to sporulation; Phase-III: sporulation; and Phase-IV: spore maturation and cell lysis (Berbert-Molina et al. 2008). More than 150 genes of exhibiting insecticidal nature have been identified from *Bt δ*-endotoxins family of proteins (Crickmore et al. 1998). These crystalline (cry) proteins remain inactive until the exposure to alkaline contents (pH >9.5) of insect mid gut, solubilize them (Milne and Kaplan 1993) and ultimately liberating *δ*-endotoxins proteins.

7.3.4. Host range of *B. thuringiensis*

Different commercial products of *B. thuringiens*is in use for crops, forests and aquatic system not necessarily contain *β*-exotoxin. Most of the *B. thuringiensis* products registered against insect pests contain Cry toxins (also known as *δ*-endotoxins). Normally, a single Cry protein works perfectly against a single order and sometimes against several families within an order. The Cry2 is an exception to this fact as it exhibits insecticidal nature against several families of Diptera and Lepidoptera (Schnepf et al. 1998).

Most of the commercial *B. thuringiensis* products or purified Cry toxins formulated for lepidopterous insects are non-hazardous to a vast variety of non-target organisms (Sims, 1997). However, non-target lepidopterans are mostly at risk in *B. thuringiensis* treated plants particularly in forests (Herms et al. 1997). For instance, the aerial spray of *B. thuringiensis* subsp. *kurstaki* (*Btk*) to control gypsy moth was found to be lethal to non-target Lepidoptera 3000 m away from treated site (Whaley et al. 1998). However, no or negligible effect was found for aquatic habitats in *Bt* treated sites when Kreutzweiser et al. (1992) demonstrated high concentrations of *Btk* on drift and mortality of Ephemeroptera, Plecoptera, and Trichoptera. Predators that preyed upon *B. thuringiensis* treated hosts were not found susceptible except the *Chrysoperla carnea* (Stephens). So in this regards, it would rather be justified statement to declare *B. thuringiensis* toxin rather safe, specific in action and compatible to non-target individuals.

7.4. Viruses

The name virus is basically derived from the Latin word ‘venome’ meaning poisonous fluid. When litreally defined, it is an infectious entity with non cellular features exhibiting either RNA or DNA, encased in a proteinaceous coat and capable of reproduction in living cells only. Generally viruses make use of host’s biosynthetic machinery for their replication to get transferred themselves to other cells of their host’s body.

7.4.1. Entomopathogenic viruses

Viruses particularly the baculoviruses also constitute an important component of microbial control program of insects. They comprise the most diverse group of entomopathogenic viruses which have been found exclusively on insect populations, especially within the insect order Hymenoptera, Coleoptera and Lepidoptera.

7.4.2. History

Diseases related to entomopathogenic viruses are known since the 16th and 17th century when Vida in 1557 discovered the Nuclear polyhedrosis virus (NPV) causing *Jaundice or grasserie* disease in silk worm moths *Bombyx mori* L. (Lepidoptera: Bombycidae) (Steinhaus 1975). In 1856, two Italian scientists Maestri and Corline described the refractive occlusion bodies in jaundiced larvae of silk moth. Bolle (1906) demonstrated that these refractive occlusion bodies were the causative agent of viral transmission in healthy animals and mentioned if refractive bodies were removed before inoculum the jaundice did not occur. Glaser (1918) was first who mentioned the nuclear polyhedrosis as a filterable virus and later published his work in Science. By 1926, French investigator Andre Paillot (Paillot 1926) discovered first time granuloviruses which were found in cabbage butterfly *Pieris brassicae* L. (Lepidoptera: Pieridae) and was characterized by a large number of small granules. Likewise, Ishimori (1934) described another disease in which host replication site of occlusion bodies were cytoplasm rather than nucleus (Cypoviruses). The invention of electron microscope makes many invisible objects visible and allowing Bergold and Suter (1959) to observe the occlusion bodies with in the crystalline matrix and they published an article on electron micrograph of NPV in the first volume of Journal of Invertebrate Pathology (Arif 2005). During 1970s and 1980s significant advances were made on the genetics of entomopathogenic viruses, especially baculoviruses.

7.4.3. Classification

The classification of viruses is based on several factors such as the type of nucleic acid (i.e. single stranded or double standard RNA or DNA), nucleocapsid symmetry and size (i.e. isosederal or oval etc.), presence or absence of occlusion body around the viron, host range, replication site and many others. The naming of entomopathogenic viruses followed the same criteria set by International Committee on Taxonomy of Viruses (ICTV). In general, viruses are classified on the basis of nucleotide sequence which not only distinguish the viral species, but also establish their evolutionary relationship among the viruses with in the same group. Insect viruses are named in acronym, according to their host and viral group to which they belong, for example *Autographa californica* (Speyer) multi-nucleopolyhedrovirus (AcMNPV), *Cydia pomonella* (Linnaeus) granulovirus (CpGV) and *Orycetes rhinoceros* (Linnaeus) nudivirus (OrNV).

7.4.4. Some important groups of entomopathogenic viruses

7.4.4.1. Nudiviruses

Nudiviruses are single stranded RNA viruses formed as rod shaped non occluded viron which was previously classified in single genus (baculovirus) and family baculoviridae. But after the sixth report of International Committee on Taxonomy of Viruses (ICTV), taxonomy status of non occluded viruses has been changed and placed in a separate family Nudaviridae (Murphy et al. 1995). This group included three viruses *Orycetes rhinoceros* nucleovirus (OrNV), *Helicoverpa zea* (Boddie) nucleovirse (HZNV-1) and *Gryllus bimaculatus* De Geer nucleovirus (GbNV) (Huger et al. 1985). All these viruses are similar in terms of replication which takes place in the cytoplasm and later spread into other tissues and organs (Huger et al. 1985; Huger and Krieg 1991), but different in mode of transmission. Both OrNV and GbNV inoculum transmitted orally (Huger *et al.* 1985) but HZNV-1 transferred through the reproductive system of both infected male and female of *Helicoverpa zea* Boddie (Lepidoptera: Noctuidae).

7.4.4.2. Cypoviruses

Members of the family Reoviridae have wide range of hosts including vertebrate and invertebrates. Insect specific cyproviruses isolated from more than 250 different species of insects belonged to order Lepidoptera, Diptera and Hymenoptera (Hukuhara and Bonami 1991). They contain a double stranded linear RNA molecule consisting of 12 lateral projections on non-enveloped isohedral viron, occluded with in the polyhedrin protein which has different amino acid sequence from polyhedrin and granulin protein of Baculoviruses (Arella et al. 1988). Cypovirus infection start when larvae consume the virus infected leaf, viron enter into the midgut columnar cell through plasma membrane and replicate only within these cells (Tan et al. 2003). Infections by cypoviruses are chronic in nature and often lead to larval retardation, un-matured adult and transfer of disease from infected to healthy ones (Nagata et al. 2003; Bellonick and Mori 1998).

7.4.4.3. Entomopoxyviruses

Entomopoxyviruses were discovered by Vago (1963). Early research shows its close association with orthoviruses on the basis of morphology but differentiated being progeny virons occluded in proteinaceous matrix after replication (Arif 2005). Entomopoxyviruses belong to family poxyviridae, have double stranded DNA molecule, formed brick shaped virons occluded in spheroid shaped occlusion bodies. Due to the wide host range, *entomopoxyviruses* are divided into two sub-families i.e., Chordopoxvirinae (vertebrate viruses) and Entomopoxvirinae (insect viruses) (Faulkner et al. 1997). Entomopoxyvirinae is further divided into three genera: Alphaentomopoxyvirus (specific to Coleoptera), Betaentomopoxyvirus (specific to Lepidoptera and Coleoptera) and Gammentomopoxyvirus (specific to Diptera).

7.4.4.4. Baculoviruses

The potential role of Baculoviruses in pest management has stemmed after their frequent isolation from insect host. Baculoviruses have two distinct phenotypes on the basis of structure; the occlusion derived viron (ODV) and budded viron (BV)

(Henderson et al. 1974; Summerson and Volkman 1976). The occlusion derived viron are embedded inside the matrix, mostly initiate the infection processes of baculoviruses from cell to cell and having single or multiple nucleocapsid per viron in parallel pattern (Adams and McClintock 1991). On the other hand, the budded viron transfer Baculovirus infection from insect to insect having single nucleocapsid per viron (Summerson and Volkman 1976). The family baculoviridae has double stranded circular DNA molecule, after removing the non-occluded DNA viruses from occluded DNA baculovirus, baculoviridae comprises of two genera Polyhedrovirus and Granuloviruses (Murphy et al. 1995). The cuboidal shaped Nucleopolyhedrosisviruses (NPVs) have occlusion body of 0.4 to 2.5 µm in size visible under electron microscope (Moser et al. 2001; Shapiro et al. 2004). In contrast, granuloviruses have ovocylindrical shape, occlusion body of 0.13 to 0.50 µm in size and cannot be seen under electron microscope (Tanada and Hess 1991). However, sequences of NPVs isolated from different hosts showed that they are polyphyletic (Herniou et al. 2004) which subdivide the family baculoviridae into four genera (Jehle et al. 2006): alpha baculoviruse (Lepidopteran specific genus NPV), beta baculoviruse (Lepidopteran specific genus GV), gamma baculovirses (Hymenopteran specific genus NPV) and delta baculoviruses (Diptera specific genus NPV).

7.4.5. Mode of infection

7.4.5.1. Primary infection

Primary infection of baculovirus is initiated when occlusion body (OB) are ingested by the susceptible larvae during feeding on contaminated foliage. The occlusion body (OB) desiccated in the high pH (<7) of midgut lumen and liberate the occlusion derived virion (ODVs) (Vega and Kaya 2012; Rohrmann 2008). The encapsulated viron enter into peritrophic membrane of midgut columnar cells and bind to the tip of microvilli (brush boarder membrane of cells). After fusion between cytoplasm and virus membrane (Faulkner et al. 1997; Haas-Stapleton et al. 2004), nucleocapsid get released into the cytoplasm and move by means of actin polymerization. Some nucleocapsids are transported into the nucleus and uncoat the viral DNA which express the early gene glycoprotein encoding the enveloped budded viron (BV) (Rodriguez et al. 2012).

7.4.5.2. Secondary infection

Systematic infection from cell to cell is accomplished by budded viron (BV) which are produced in midgut (Rodriguez et al. 2012). Budded viron of baculovirus enter in to insect cells through Clathrin-Mediated Endocytosis pathway, followed by internalization of BV into low pH endosome prompting the fusion between BV and cellular membrane (IJkel et al. 2000). The released nucleocapsid move into cytoplasm through actin polymerization and are ultimately transported to the nucleus. The electron dense structure formed in the nuclei called virogenic stroma where viral DNA transcription and translation can occur and the progeny nucleocapsid is released (Kawasaki et al. 2004; Vega and Kaya 2012). The nucleocapsid gets enveloped in the peritomial region to form the occlusion derived viron (ODV). In most of pathogenic viruses, break down of host tissue occurs from the expression of cathepsin proteins and virus-encoded chitinases (Ohkawa et al. 1994; Slack et al. 1995). As a result of expression of viron encoded chitinase and cathepsin proteins tissue degradation of host occurs. OB is released in to the environment after the breakdown of insect cuticle and approximately 1×10^9 OB are released from the single host larvae and remain in the environmental reservoir over a long period of time, until eaten by any other susceptible larvae to resume the infection (Evans and Harrap 1982).

7.5. Nematodes

Nematodes belong to the kingdom Animalia. These are non-segmented animals generally referred as roundworms, eelworms or threadworms due to their usually cylindrical and elongated body. Their size generally ranges from few mm (0.1 mm) to several meters in length. The female of some species, however become swollen at maturity and have pear shaped or spheroid bodies. The nematode body is more or less transparent. It is covered by a colorless cuticle, which is usually marked by striations or other marking. The cuticle molt when a nematode goes through the successive juvenile stage. The cuticle is produced by the hypodermis which contains living cells and extends into the body cavity as four chord separating four bands of longitudinal muscles. Numerous species of nematode attack and parasitize human and animals in which they cause various diseases. Several species are characterized of feeding on living plants, obtaining their food with spear or stylet and become a reason for numerous diseases of plants worldwide.

7.5.1. Entomopathogenic nematodes

The widely used term entomopathogen both in parasitology and pathology referred to microorganisms which have the ability to cause diseases in insect host (Onstad et al. 2006). Among the seven families of insect parasitic nematode, the nematode in the family Steinernematidae and Heterorhabditidae have evolved the symbiotic association with insect pathogenic bacteria. Entomopathogenic bacteria are those who have the LD_{50} of 10000 cells are less. This means that an inoculum of 10,000 bacterial cells required to kill the half population of tested insect (Bucher 1960). The bacteria in the genus *Xenorhabdus* makes mutualistic interaction with Steinernematidae and Photorhabdus with Heterorhabditidae.

7.5.2. History

Gotthold Steiner was the first who described the entomopathogenic nematode as *Aplectana kraussei* (now *Steinernema kraussei*) (Poinar 1983). Glaser and Fox (1930) isolated the second nematode *Neoaplectana glaseri* (now *Steinernema glaseri*) from Japaneese beetle, *Popillia japonica* and Steiner placed in the family Oxyuridae. The importance of bacteria in the life cycle of nematode was described by Gaugler et al. (1992). He showed that when trying to develop axenic (without any organism) culture of *S. glaseri* for the control of insect pest, the bacterial contamination was tolerated by nematodes (Lewis and Clarke 2012). Probably the contaminated bacteria were *Xenorhabdus poinari* a symbiont of *S. glaseri.* Later he developed the axenic culture of *S. glaseri* to control the Japanese beetle, but success was limited (Lewis and Clarke 2012).

The first symbiotic relationship between nematode and bacteria was described by Dutky (1937) and he noticed the antibiotic properties of bacterium associated with *Steinernema carpocapsae* (Nemata: Steinernematidae), which explained how it could destroy foreign bacteria that invaded the insect cadaver containing the developing nematodes. Since then several antibiotics, including xenorhabdins, xenocaumacins, hydroxystilbenes, indole derivatives, and anthraquinone derivatives, were recovered from cultures of *Xenorhabdus* and *Photorhabdus* (Walsh and Webster 2003).

7.5.3. Classification

Out of 23 insect parasitic nematode families seven have the ability to serve as the potential biocontrol agent. These are, Allantonematidae, Heterorhabditidae, Mermithidae, Phaenopsitylenchidae, Sphaerulariidae (***Order:*** Tylenchida); and Steinernematidae (***Order:*** Rhabditida) and Tetradonematidae (***Order:*** Stichosomida). Recently only few of them are in commercial production as microbial insecticide particularly Heterorhabditidae and Steinernematidae. The spectrum of biocontrol potential of most of nematodes is limited because of problems associated with their culturing except the Tylenchid, Deladenus (Beddingia) and Siricidicola, which are still in convention for inoculative control of wood wasp species in Australia (Bedding 1993), the microbial control potential of other nematode species is rather limited because of problems with their culture.

7.5.4. Mode of infection

The infective juvenile stage (IJs) is the only free living stage in entomopathogenic nematodes (EPNs) which have the ability to infect new host. Mostly nematode based commercial formulations have this IJs stage to control insect pest but some formulations contain infected insect host. There are six life stages in EPNs, first egg stage, four juvenile stages and last one is adult stage. The third stage is IJs which is similar to dauer stage of *Caenorhabditis elegans* (Maupas) (Rhabditida: Rhabditidae). The term dauer meaning “enduring” and in dauer stage nematode survive external harsh condition without nourishment. The IJs enter the host through anus, mouth and spiracles. But in some cases both Heterorhabditidae and Steinernematidae makes a thin hole in host cuticle. After successful penetration the IJS release the bacteria in host haemolymph. The bacteria produced toxin which kill the host (Lewis and Clarke 2012). The main difference between Heterorhabditidae and Steinernematidae is that first IJs in Heterorhabditidae become hermaphrodites adult but amphimictic in the following generation. But in case of Steinernematidae all adults are amphimictic except in *Steinernema hermaphroditum* in which adult are hermaphrodites in first generation (Koppenhöffer 2007).

7.5.5. Host range

The main reason for their failure is poor understanding of nematode ecology. A significant reduction in pest population has been achieved by corresponding biological and ecological studies of nematode and target pests. The similarity in biological and ecological consideration becomes essential for nematode and their hosts if some output has to be brought out in nematological applications. The most important considerations that have to be met to make nematode applications as efficient control strategies are the foraging efficiency and temperature dependency of nematode species. Further the ease of access to its host and suitability to host is another factor required by nematodes.

Applications of EPN have been made against soil insects, cryptic insect, aquatic insect and on foliage insect (Koppenhöffer 2007). Mostly success with nematode has been achieved against soil insects because soil is the natural habitat of nematode which acts as buffer for its IJ stages.

The IJ stages of nematode enter the host through mouth, anus and spiracles but in some insect's nematodes are not accessible to these openings (Koppenhöffer 2007). For example in case of wire worm, the blockage of mouth by oral filters, in sucking and young instars of chewing insects, narrow passage of mouth parts, constriction of anus in wireworm, covering of spiracles with septa or sieves in scarab beetle or very narrow passage in some dipterous and lepidopterous insects. The restriction to nematode entrance could be due to some other obstacles in intersegmental membranes, fore and hindgut cuticular linings, or the peritrophic membrane. Aggressive grooming or evasion behavior may also hinder nematode infections in many cases (Gaugler et al. 1994). The formation of impenetrable cocoons or soil cells seems to be another limitation in the use of nematodes for insect control (Eidt and Thurston 1995). Social insects as a whole appear to be susceptible host to nematode infections but they cater these pathogenic invasions by isolation, removal of infected individuals, social grooming, and translocation of colony (Klein 1990; Gouge 2005).

7.6. Conclusion

Arthropods are dominant creature in the world which has millions of described species. Among them a vast majority is beneficial to human beings. While small percentage is considered pest and vector species which cause number of diseases in human beings and devastate the crops, cause losses about 18% by cutting down the world annual crop production, contribution of losses in stored grains appears to be 20%, with total devastation of around 100 billion US$ every year. Worldwide inter-dependence of markets for agricultural produces have gradually brought to forefront the need to develop agricultural practices that moderate the hazards of insecticide residues on the environment and that result in bio-rational products that are safe for human consumption. Frantic efforts are being focused towards non-chemical and sustainable plant protection methodologies. The greater concerns of synthetic chemicals to human, its belongings and environment have highlighted the importance of "entomopathogenic" microorganisms as a reality. Amongst the virus, bacteria, nematode and fungi are applicable, well studied and widely used in pest control. They have shown meritorious results in the management of various insect pest populations. Numerous entomopathogens are employing for the control of insect pests in various agricultural systems. New research suggests that they deploy various mechanisms and their effectiveness is affected by plenty of biotic and abiotic factors. Naturally occurring non-pathogenic endophytic and epiphytic microorganisms may also affect the effectiveness of entomopathogenic fungi against plant pathogens. Detecting deleterious and beneficial relationships with other microbes may permit for the manipulation of agricultural ecosystems to enhance the synergistic interactions. Research has also been focused to examine the spore surface chemistry of entomopathogenic fungi solving problems of fungal formulations to improve the shelf life, physical characters and biocontrol efficacy of the product.

The greater concern of future research regarding commercial *Bt* products is to develop newer products with increased host range, effective infection cycle, improved shelf life, enhanced persistence and decreased cost of production. Studies at molecular level are assisting to identify and isolate the toxins and virulent factors responsible for host infection.

Expressing fusion proteins has successfully broadened the host range of entomopathogenic viruses is another area of future research. Gene silencing method RNA interference (RNAi) is another new and promising approach to control the pest population.

In vitro mass production of nematode can be increased by understanding the nutritional contribution with their symbiotic bacteria *Photorhabdus* and *Xenorhabdus*. Different rational based techniques could be used to increase the nutrients requirement of nematode for efficient recovery of IJs. Research should also be focused on the mechanisms of suppression of plant pathogenic nematodes by EPN, which will emphasize the need on the use of EPN in integrated disease and pest management systems.

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Chapter 8

Biorational Approaches in Pest Management

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Abstract

Most of the commercially available conventional and synthetic insecticides have broad range toxicity as they target those insect's systems which have physiology exactly like the higher mammals including man. That why they are imposing serious health hazard threats (mutagenic, carcinogenic and teratogenic effects) on human being due to possessing very high mammalian toxicity, long-term residual persistency and high magnification potential. They are also creating many other serious problems like ecological backlashes in pest species, environmental pollution and degradation, threat to biodiversity conservation and loss of beneficial fauna (predators, parasites pollinators etc.). There is a need to explore and develop biorational molecules/products which would tackle most of the issues associated with conventional insecticides. Need is to develop analogues of such biorational and highly target specific biomolecules through modern biotechnological molecular approaches. Biorational products/approaches are based on the growth and development as well as communication system of insects which is quite different from higher animals and human being. These products have great potential for

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replacing the persistent conventional insecticides, confirming effective cost-benefit-ratio, tackling ecological backlashes and ensuring food security with safe environment and enhanced exports. In the new era of biotechnology, most of the issues associated with these biorational products have been solved and these products are not only winning the reliability of the market and end user; but also demonstrating their worth and potential in sustainable IPM program. This chapter focuses on the perspectives and prospects of biorational approaches in sustainable Integrated Pest Management (IPM) program of economic crops.

Key words: IGRs; Semiochemicals; Biorationals; Pheromones; Allelochemicals; pest management

8.1. Introduction

The term "Integrated Control" was introduced by Stern et al. (1959). This was the era characterized by insect pest control with broad-spectrum, conventional insecticides including organochlorines (OCs), organophosphates (OPs), pyrethroids and carbamates, which were mostly neurotoxic. The use of these broad-spectrum insecticides led to environment degradation, problems of ecological backlashes and public health associated issues and the public criticism demanding alternative pest control tactics. Then there came the concept of IPM approaches for the pest management. The concept of IPM, later on, experienced a paradigm shift towards "risk reduction approaches" reducing impacts of pests and pest management tactics on human possessions and ecology. Such reduced risk agents and approaches are crucial and fundamental means of strengthening IPM strategies to address the challenges of a society (Ishaaya 2003; Ishaaya et al. 2005).

Nutritional requirements of insects and vertebrates are almost similar. Likewise, physiology and biochemistry of digestive and nervous systems as well as metabolic processes and reactions involved in biosynthesis of proteins and nucleic acids of insects also fundamentally similar to vertebrates. However, the aspects of insects' physiology and the anatomy that are different from those of vertebrates include the structure of their integument and their endocrine and communication systems. Majority of the insecticides belonging to different classes for managing insect pests are neurotoxicants and highly non-selective; because they impose same toxic effects on higher animals including man as they have on insects (Dhaliwal and Arora 2003). This emphasizes on the development of selective insecticides fromthose molecules which block, disrupt or inhibit any of the pathway bridging their biosynthesis, storage, release, transport and reception in insects' cuticle, endocrine and chemical communication systems. The biochemics, which are involved in other pharmacokinetics and detoxification mechanisms of insecticides in insects and are different from those of vertebrates cane be use to dvelop insecticide molecules. Such molecules when synthesized in form of insecticide formulation will highly be lethal and target specific affecting the growth, behavior and chemical communication systems of insects.

The pesticides have been classified on the basis of their chemical structure [e.g., carbamate, Organochlorines (OCs), Organophosphates (Ops), Pyrethroids], mode of action [e.g., narcotic, synaptic, axonic, muscles, and physical poisons; IGRs (Insect Growth Regulators), antifeedants, etc], mode of entry (e.g., stomach, contact, systemic, translaminar fumigant insecticides), source of origin (e.g., 'natural', botanical, animal, synthetic, analog etc.). However, the authorities are still unable to decide the actual definition, fate and place of term "biorational pesticides". The term "biorationals" has been derived from two words, biological and rational and denote to such pesticides that have been derived from some natural source and impose minimum or no adversarial threats on the environment or beneficial organisms (Ware 1989). Historically, Carl Djerassi (Djerassi et al. 1974) used the term "biorationals" for the first time for pheromones, insect hormones, and hormone antagonists. However, he did not proposed any particular definition of "biorationals" except describing their properties like their species-specificity, active lethality at low concentrations and low persistency or toxicity to non-target vertebrates. Since then, the term "Biorational pesticides" is still ambiguous and confusing. Some consider microbial or plant origin molecules as "biorational pesticides"; a few speciously contemplate organic pesticides as "biorational pesticides"; while others categorize plant or insect oriented natural biochemicals and their synthetic analogs as "biorational pesticides". Some define biorationals as biologicals or botanicals which are highly compatible with living systems of human being. According to a viewpoint, insecticides are termed as biorationals if they denote pragmatic and empirical compatibility in one system but categorically do not impose such effects in another system (Ellsworth and Martinez-Carrillo 2001; Naranjo et al. 2003, 2004). Still there is a group that emphasizes that biorational agents should have limited or no affect on non-target organisms, including humans and their domestic plants and animals (Diver and Hinman 2008). Another term "reduced-risk pesticides" synonym to "biorationals" was introduced in 1997 for those pesticides that augment and accelerate the effectiveness of IPM program economically imposing least or no toxic jeopardies to human health, non-target organisms or environmental resources (Uri 1998). No established definition of "biorationals" exists in litreature. Different scientists define the term "biorational pesticides/biorationals" in different way. For example, according to Environmental Protection Agency (EPA) the term "biorationals" is practically synonym to term "biopesticides" which have low risk, are derived from natural sources including plants, animals, bacteria and certain minrals and are divided into "microbials", plant-incorporated protectants (PIPs) and biochemical (Rosell et al. 2008). Stern et al. (1959) introduced the term "Selective insecticide" and defined it as "an insecticide which kill the pest individuals but spares much or most of the other fauna, including beneficial species.". Plimmer (1985) introduced process-oriented definition of "biorational" and explicated that "biorational is the exploitation of knowledge about plant or animal biochemistry in order to synthesize a new molecule which acts at a particular site or blocks a key step in a biochemical process". Bowers (2000) modified and improved process-oriented definition and concept of "biorational" by incorporating the concept of selectivity. According to him, "biorational is the exploitation of knowledge about plant or animal biochemistry in order to synthesize a new molecule designed to act at a particular site or to block a key step in a biochemical process; however, these pest-suppressive molecules and their associated methodologies should disturb those discrete evolutionary aspects of pest biology and behavior that separate invertebrate and microorganism from human biology." According to Ware (1989), biorational pesticides include derivative of a variety of biological origin (including bacteria, viruses, fungi and protozoa) and chemical analogues of natural biochemicals (like pheromones and insect growth regulators) that are environmental-friendly and meticulously resemble to chemicals of insects and plants origin. According to Pathak and Dhaliwal (1986) and Dhaliwal and Arora (2003), "Biorational Control" involves the utilization of chemicals that suppress insect populations in a control system by modifying behavior, disrupting growth and impeding reproduction of the insects populations. Generally and operationally, the biorational pest management involves the substances or processes that execute diminutive or no adverse consequences to the environment and non-target organisms (humans, beneficial fauna and flora etc.); however, impose lethal, suppressive or behavior modifying effects on a target organism and augment the specific control system. A brief categorization of the biorational pesticides is illustrated in Figure 8.1.

This chapter focuses on the discussion of safer, ecofriendly and target-specific biorational insecticides based on neuropeptides, neurotransmitters and growth hormone in insects, venomic-peptides of parasitoids and natural-enemy-, plant- and herbivore-derived semiochemicals, which have been developed by using modern biotechnological approaches.

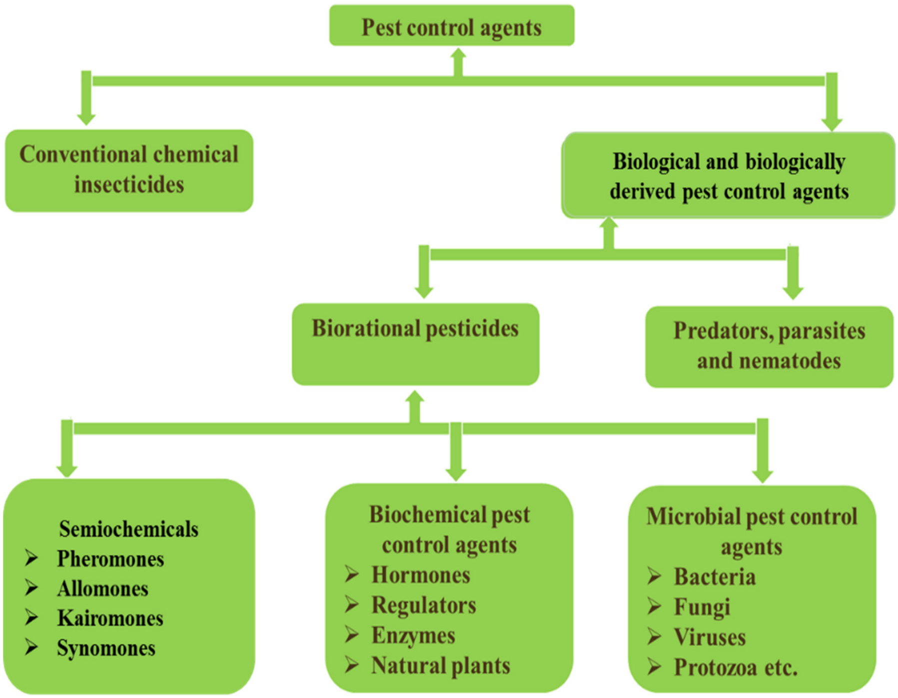


Fig. 8.1 Categories of biorational pesticides

8.2. Insect growth based approaches

These approaches include utilization of IGRs (Insect Growth Regultors) which do not have direct lethal or deadly effects on insects; rather, they disrupt the normal mechanisms of insects' growth and development. These biorational insecticides affects the growth and development in two ways: they either; 1) interrupt with the mechanism of normal cuticle formation by inhibiting or accelerating chitin synthesis, chitin degradation or sclerotization process in insects; or 2) inhibit or accelerate the secretion and action of insects' growth hormones. IGRs are generally categorized into two major classes (Dhaliwal et al. 2006) on the basis of their mode of action.

1) IGRs interfering with the cuticle formation mechanisms (e.g., Chitin synthesis inhibitors, chitin degradation inhibitors, cuticle sclerotization disrupters etc.)
2) IGRs interfering with the secretion and actions of insect growth hormones (e.g., Brain hormones, Juvenile hormones, Molting hormones, etc.)

8.2.1. Insect cuticle targeting insecticides

Main structural component of insect cuticle is the chitin which is composed of many units of N-acetyl-D-glucosamine. The mechanisms of biosynthesis and biodegradation of cuticle and cuticular sclerotization are considered perfect targets for idealizing any insecticide as highly target specific and safe for human (Dhaliwal and Arora 2003; Dhaliwal et al. 2006). A large number of natural molecules or their analogues possessing such mode action have been developed and commercialized as insecticides (Table 1). Insect cuticle based biorational IGRs are categorized into following types:

8.2.1.1. Chitin synthesis inhibitors

Chitin synthesis inhibitors (CSI) belong to that class of biorational insecticides which were unexpectedly developed in 1970 when insecticidal property of benzyolphenyl urea (BPU) analogues was confirmed by Philips-Duphar Company. The first most CSI analogue (DU 19.111) was developed by combining two herbicides (dichlobenil and diuron) (Dhaliwal et al. 2006). The target site of CSIs is the polymerization step of chitin-biosynthesis catalyzed by chitin-synthase. At this site, they modify the permeability of membrane and block the availability of substrate at the active site of membrane bound enzyme (chitin synthase) (Mayer et al. 1990; Dhaliwal and Arora 2003). CSI disrupts the biosynthesis of chitin which makes a 30-60% portion of the insect exoskeleton (cuticle) and impairs the development of new exoskeleton in larval instars at molting stage. The insects without normal or with abnormal exoskeleton cannot survive and die within short period of time due to rapid desiccation or excessive dehydration from larval body. The major groups of CSI biorationals include benzoylureas, triazine/pyrimidine derivatives, buprofezin and plumbagin. CSIs do not induce toxicity until or unless these are ingested with food. Thats why, most of the CSIs are innocuous and safe for bees, predators and parasitoids (Tomlin 2000) because these insects do not ingest the CSI-treated foliage. Rest of the properties and characteristics of CSIs are illustrated in Table 2.

8.2.1.2. Chitin degradation inhibitors

Steps of chitin degradation and enzymes involved are reported as source of target specific biorational IGRs or preparation of their analogues which may act as chitin degradation inhibitors (CDIs). In insect's growth, specifically at the time of ecdysis, chitin degradation is as much important as the chitin biosynthesis because degradation process not only makes the old cuticle more frail and delicate along epistomal suture (ecdyseal cleavage line) to facilitate the rapturing of old cuticle and emergence of insect but also provides degradative products which, after their recycling, are used in the synthesis of new cuticle. If chitin degradation is inhibited, the old cuticle remains hard enough not to facilitate rupturing, ecdysis does not occur and insect dies inside the old skin (exuvium). Similarly, synthesis and deposition of new cuticle is not possible that leads to the death of new instar due to excessive desiccation and dehydration. All the process of chitin biodegradation is regulated by chitinolytic enzymes (chitinase and chitobiase) which seem to be striking target for developing CDI analogues with enough biological activity quite similar to those natural biomolecules which regulate chitin degradation in insects. Similarly, the genes translating chitinolytic enzymes during chitin degradation process are also promising targets for genetic engineering of crops against phytophagous insects (Pedigo 2003; Chapman 2013). However, no bio-molecule or analogue has been developed, synthesized or commercialized as insecticide yet that possess chitin degradation inhibiting properties (Dhaliwal and Arora 2003; Dhaliwal et al. 2006). Some laboratory studies documented the identification of some molecules having CDI activity. For example, Shahabuddin et al. (1993) reported allosamidin as a specific chitinase inhibitor.

8.2.1.3. Sclerotization inhibitors or accelerators

In insect's cuticle, about twenty (20) different types of proteins, phenolic compounds and other constituents are covalently stabilized by sclerotization mechanism (Hopkins and Kramer 1992) which is a very complicated and intricate process regulated by a hormone "Bursicon" in insects during postecdyseal processes (Pedigo 2003). The inhibition or acceleration in this process leads to abnormalities (failure of sclerotization or unusual and infrequent hardening) in larval or pupal cuticle making it more vulnerable to desiccation. In this situation the insect die due to excessive dehydration. Different types of neurosecretory enzymes are involved that accelerate and inhibit the process of sclerotization when required in the insect growth stage. These postecdyseal processes and associated enzymes are the appropriate target for developing target specific biorational analogues as IGRs with sufficient sclerotization inhibiting or accelerating activities. The examples of insecticides having sclerotization disrupting properties include MON-0585 (only commercialized sclerotization inhibitor developed by Monsanto), α-methyl DOPA and Cryomazine (Dhaliwal et al. 2006). The detailed properties and other characteristics have been illustrated in Table 2.

8.2.2. Insect growth hormones based insecticides

All growth and developmental processes in insects are controlled by a variety of hormones secreted by ductless glands of endocrine system. The insect's growth regulating hormones are secreted from various neurosecretory cells (ductless glands) of different parts of nervous system and have specific role in postembryonic growth and metamorphosis. These hormones include Brain Hormone (BH) or Prothrocicotropic Hormone (PTTH), Moulting Hormones (MH), Juvenile Hormones (JH), Eclosion Hormone (EH) and Tanning Hormone (TH) (Pedigo 2003). BH or PTTH is produced by the neurosecretory cells of brain and triggers the prothoracic glands which resultantly secrete ecdysone (a molting hormone). MH controls the molting process of immatures (larvae, nymphs or naiads). JH is secreted by corpora allata (gland) that control the juvenile characters and type of molt in insects. A high concentration of JH in haemolymph triggers the larval molting into next larval instar, its low concentration elicits larval molting to pupation and absence of JH in haemolymph stimulates pupal stage to molt into adult (eclosion). JH is almost absent in the pupae, but present in adults where it persuades vitellogenesis and controls reproduction during the reproductive stage of the insect (Eto 1990). EH is secreted by neurosecretory cells of brain; whereas, TH by neurosecretory cells of brain or abdominal ganglia. EH and TH are responsible for process of eclosion and sclerotization in insects, respectively. This endocrine system and associated hormones are promising biochemical specific-sites for developing biorational biochemical-agents that, when interfere with the actions of these biochemical specific-sites, disrupt the physiology of growth processes, induce abnormalities in growth and bring mortality in insects (Ishaaya and Horowitz 1998; Ishaaya 2001; Dhaliwal et al. 2006). The biomolecules of these hormones and their analogues are safe and insect-specific; but their utilization in pest management is limited because of: 1)their linear nature and high vulnerability to proteolytic degradation, 2) problems of their penetration into biological tissues, 3) vulnerability to quick photo-degradation and 4) complications in designing their antagonists (Altstein et al. 2000; Horowitz et al. 1995). However, these limitations are addressable by the exploitation of modern biotechnological approaches; for examples, i) synthesis of simpler peptide analogues with high photostability, penetration and agonistic or antagonistic properties to cuticle and target tissues of insects, ii) Insertion of neuropeptide regulating genes into host-plant's tissues by genetic engineering to produce GM-crops resistant to insects like Bt-crops, iii) large-scale economical production of neuropeptides by vector-mediated and vectorless gene transfer technology (Dhaliwal et al. 2006).

8.2.2.1. Brain hormones based insecticides

Brain hormones are neuropeptides which are also called neurohormones. These neuropeptides are produced by central nervous systems (CNS) in form of chemical signals for controlling various metabolic events in the body of insects (Dhaliwal and Arora 2003; Pedigo 2003; Dhaliwal et al. 2006). As these neuropeptides secreted from insect's brain regulate many of the physiological functions of insect's life like development, growth, reproduction, behavior, metabolism etc., so their agonistic or antagonistic analogues can be exploited commercially for the development of biorational insecticides. Proctolin was originally an insect's brain hormone which was isolated from *Periplaneta americana* (American cockroach) in 1975 and has broad range of physiological functions (Dhaliwal and Arora 2003; Dhaliwal et al. 2006). It acts as a putative neurotransmitter and neuromodulator on oocytes for uptake of vitellogenin during oogenesis inside the reproductive system and performs neurohormonal role in insect's growth and development (Goudey-Perriere et al. 1994; Lange 2002). More than 65 such neuropeptides have been isolated and identified from different types of insects belonging to Dictyoptera, Lepidoptera, Hymenoptera and Diptera (Dhaliwal et al. 2006).

Different kinds of brain hormones are produced by the CNS and stored as well as released from neurohaemal sites in the insect's brain like carpora cardiac and corpora allata (Coast et al. 2002). A little bit detail of these brain hormones is as under:

Diuretic and antidiuretic brain hormones

The diuretic and antidiuretic hormones are diuresis controlling antagonistic hormones which promote and inhibit water loss, respectively (Spring et al. 1988). These two hormones are produced by neurosecretory cells of insect's brain and stored and released from carpora cardiac. They regulate the excretion metabolism, urine balance, water balance, postprandial diuresis, post-eclosion diuresis, excretion of excess metabolic water, clearance of toxic wastes and restricting metabolites loss by their regulated-interactive and antagonistic action on malpighian tubules and hindgut (Furuya et al. 2000; Holtzhausen and Nicolson 2007). Diuretic hormones are grouped into three main families including calcitonin (CT)-like peptides, corticotropin-releasing factor (CRF)-related peptides, and the insect kinins (Coast et al. 2002).

Eclosion hormone

Eclosion hormone is a neuropeptide secreted either by the neurosecretory cells of brain or by ventral ganglia of insects depending upon the growth and development stage of insect. It initiates a cascade of pre- and post-eclosion actions and regulates the sequence of events of eclosion (process of adult's emergence from the pupa) in insects. It is also involved, with other hormones (e.g. ecdysone), in moulting of the cuticle by immature stages (Chapman 2013).

Allatostatins

The term "allatostatins" describes those allatostatic neuropeptides which are secreted from the neurosecretory cell of brain and inhibit the biosynthesis of juvenile hormone by carpora allata. These brain hormones were isolated for the first time from the brain cells of pacific beetle cockroach, *Diploptera punctate* (Tobe 1980) and belong to Allatostatins-A (are stage/sex or species specific), Allatostatin-B (neither stage/sex nor species specific) and Lepidopteran-allatostatins families. Many researchers have isolated various members of allatostatins-A from different insects including cockroaches, crickets, grasshoppers, locust, stick-insects, blowflies, mosquitoes, lepidopteran species (*Helicoverpa* sp., *Cydia* sp. etc.), honey bees etc. and documented varying capability of inhibiting JH biosynthesis by these allatostatins depending on the donor-receiver physiological differences and development stages of insects. On the basis of their sequence homology, allatostatins-A are discussed as callatostatins (flies), helicostatins (bees), cydiastatins (moths), schistostatins (locusts) and carausiustatins (stick-insects) (Hoffmann et al. 1999). Allatostatin-B includes all non-apeptides that exhibit sequence resemblance to myoinhibiting peptides and cause 50% inhibitions of JH biosynthesis (Blackburn et al. 1995; Lorenz and Hoffman 1998). Lepidopteran allatostatins are amidated peptides (Kramer et al. 1991)

Allatotropins

These are neoropeptides which are secreted by neurosecretory cell of brain and stimulate the corpora allata to produce JH (Bogus and Scheller 1994). They belong to family of myoactive peptides and exhibits manifold neural, endocrine, myoactive and JH-stimlating role in insects (Elekonich and Horodyski 2003). The only allatotropin isolated from the brain of pharate adults of *M. sexta* moth is Mas-AT (Hoffmann et al. 1999)

Prothoracicotropic hormone

Prothoracicotropic hormone (PTTH) is a neuropeptide which is secreted by neurosecretory cells of insect's brain and triggers prothoracic gland to produce ecdysone (molting hormone) (Chapman 2003; Klowden 2007). There is need to explore or synthesize highly photostable and penetrable antagonistic analogues of PTTH having disruptive effects on ecdysone production by prothoratic gland. Some examples of such analogues are commercially available which have been discussed under heading "Molting hormone based insecticides".

Pheromone biosynthesis activating brain hormones

Pheromone biosynthesis activating hormones (PBAH) are pheromone biosynthesis activating neuropeptides (PBAN) which are produced by neurosecretory cells of insect's brain or suboesophageal ganglia near brain and triggers the pheromone glands for pheromone biosynthesis in insects. PBAH or PBAN belongs to PK (Pyrokinin)/PBAN family including Pheromonotropin (PT) and Myotropin (MT) peptides (Altstein 2004) and their quantitative production depends on the sexual form of the insects because of the differences in gene expression and functional responses of different sexual forms. There chemical nature varies from insect to insect species; for example, in *Helicoverpa zea, Pseudaletia* (*Mythimna*) *separate, Leucophaea maderae* and *Locusta migratoria Hez*-PBAN (33-aminoacid peptides) (Raina et al. 1989), *Pss*-PT (18-aminoacid peptides) (Matsumoto et al. 1992), *Lem*-PK (8-aminoacid peptides) and *Lom*-MT-II (8-aminoacid peptides) (Choofs et al. 1990) were identified as PK/PBAN peptides, respectively (Heriton et al. 2009).The aminoacid sequence as well as chemical and biological activities of PBAH or PBAN have been reported to vary consistently with the insect's species and their phylogenetic associations (Choi and Meer 2009; Choi et al. 2011).

This multifunctional PK/PBAN family of neuropeptides controls many behavioral and developmental processes in insect (Heriton et al. 2009), including mating behavior (sex pheromone biosynthesis) (Altstein et al. 1995), feeding (contraction of gut muscles) (Schoofs et al. 1991), diapause (Zhang et al. 2004; Sun et al. 2005), cuticular melanization (Altstein et al. 1996) and pupariation (Nachman et al. 1997). Using INAI (Insect Neuropeptides Antagonist Insecticide) technique, several highly potent, selective and metabolically stable backbone cyclic (BBC) antagonists of Pyrokinin/Pheromone Biosynthesis Activating Neuropeptide (PK/PBAN) were discovered. These BBC antagonists of PK/PBAN lack of agonistic role and possess sex pheromone biosynthesis inhibition properties in female insects, especially moths

(Altstein 2004; Heriton et al. 2009). Such antagonists of PK/PBAN have been reported to cause sex pheromone biosynthesis inhibition effects in females of a variety of insects (Heriton et al. 2009). For example, *Helicoverpa peltigera* females and *Spodoptera littoralis* larvae exhibited 70% inhibition in biosynthesis of sex pheromone and 100% inhibition of cuticular melanization, respectively, when treated with antagonists of PK/PBAN. Biosynthesis of pheromone in Indian meal moth (*Plodia interpunctella*) was inhibited by its *in vitro* treatment with Arylaldehyde semicarbazones and 5-aryloxazoles. Some other bioagent amine like tyramine, dopamine and octopamine act on pheromone glands disturbing sex-pheromone production (Hirashima et al. 2007). However, the potential of these agonists in pest control are not yet achieved due to many problems in commercial exploitation of these neuropeptides.

8.2.2.2. Molting hormones based insecticides

Prothoratic glands secrete hydrophilic Molting Hormones (MH) which are steroidal peptides comprising of mainly ecdysone (20-hydroxyecdysone, 26-hydroxyecdysone, 20, 26-dihydroxyecdysone), ecdysteroids and ecdysterone (Makisterone-A, 20-deoxymakisterone). These steroidal peptides regulate various physiological metabolisms of molting, growth, maturation and reproduction in insects (Dhaliwal and Arora 2003; Dhaliwal et al. 2006). .

MHs or their analogues cannot be efficient molecules for development of insecticides due to their hydrophilic nature that make these molecules non-penetrable through insect cuticle. The biosynthesis of MHs in insect body is a very complex process. In the presence of desmosterol, phytosteroids are converted into cholesterol which is then converted into MH (ecdysone). Phytoecdysteroids also play a vital role in developing MHs imbalance in insect body, promoting abnormal growth and ultimately causing death of the insect (Dhaliwal et al. 2006).

Phytoecdysteroids (steroids extracted from plants), through desmosterol-cholesterol-ecdysone conversion reaction, enhance the titer of ecdysone in the haemolymph of insects. The ecdysone produced by this conversion reaction is metabolized and excreted out of insect body very slowly creating hormonal imbalance. Some phytoecdysteroids having insecticidal activity have been isolated from different parts of plants. Triaparanol, diazacholestrol, azasterol, azasteroids, nitrogen containing steroids, and non-steroidal amines or amides inhibits the action of sterol-reductase enzyme, interrupt the desmosterol-cholesterol- ecdysone conversion reaction and biosynthesis of ecdysone leading to disruption of growth and development of insects. Phytoecdysteroids extracted from the seed of *Diploclisia glaucescens* Diels and phytoecdysterone isolated from mature stems of *D. glaucescens* exhibit insecticidal activity against *Ostrinia nubilalis* (Hubner) larvae (European corn borer) and *Aphis craccivora* Koch. (Groundnut aphids). Similarly, ecdysteroids isolated from dried parts of *Ajuga reptans* L. and *A. remota* act as MH mimic and demonstrate strong disrupting effects on the growth and metamorphosis of Mexican bean beetle, *Epilachna varivestis* Mulsant. However, such phytosteroids are not available commercially due to high cost required for their production and commercialization, quick photo-degradation and many other problems already mentioned (Dhaliwal et al. 2006).

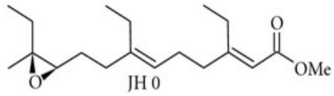
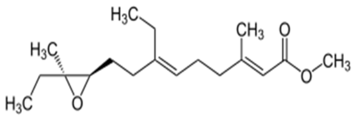
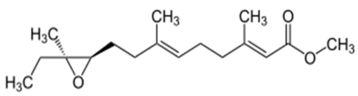
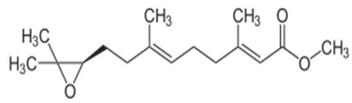
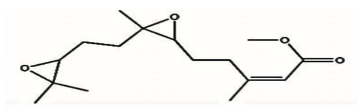
Exploration or synthesis of MH Agonists/antagonists or Phytoecdysteroids can lay the foundation of biorational biomolecules for ecofriendly management of various insect pests. The MH agonists/antagonists can be potential biomolecules for developing new insecticides having activity of disrupting the ecdysteroid receptor and normal growth in insects (Dhadialla et al. 1998; Harada et al. 2011). MH-agonists are mimics of MH and forcefully trigger the molting insects towards premature molting leading to feeding cessation and finally death of molting insects. They also enhanced mortality of eggs and reduce fecundity as well as rate of reproduction. The commercially available MH-agonists include Tebufenozide, Chromafenozide, Halofenozide and Methoxyfenozide which are Bisacyllhydrazines (BSH). MH-Antagonists (MHA) are those MHA-analogues which disrupt the production of PTTH and inhibit the effects of MH (Ecdysone). So far, two MHA based insecticides, i.e. Diofenolan and azadirechtin, are available commercially (Table 8.4).

8.2.2.3. Juvenile hormones based insecticides

Juvenile hormones (JHs) belong to acyclic sesquiterpenoids (class of terpenes having the molecular formula $C_{15}H_{24}$) that regulate many physiological and metabolic aspects of insect life like diapause, development, reproduction, polyphenisms (Wyatt and Davey 1996; Li et al. 2007; Parthasarathy et al. 2008), embryogenesis, molting and metamorphosis, pigmentation, caste differentiation, communication, migration/dispersal, silk production, and phase transformation with main function of maintaining larval status (Tunaz 2004). JHs isolated and identified in insects so far are categorized into JH_0, JH_I, JH_{II} and JH_{III} (Table 8.1). JH_{III} is the most commonly found juvenile hormone in most of the insects (Judy et al. 1973). However, JH_0, JH_I and JH_{II} are the juvenile hormones which have specifically been isolated and identified from butterflies and moths. Another bisepoxide form of JH_{III} has been isolated and identified from dipterans (true flies) and categorized as JHB_3 (Richard et al. 1989). Because of their selective morphogenetic effects, these JHs have been focused as impending stand-ins for synthetic non-selective insecticides. As compared to natural JHs, JHA (Juvenile Hormone Analogue) are more stable. Examples of such MHAs which have been commercialized include methoprene, hydroprene, kinoprene, triprene, fenoxycarb, pyriproxyfen, epofenonane and dayoutong (Table 8.4). Some plant products also have JH activity. For example, juvabione (methyl ester of todomatuic acid) and its analogue, dehydrojuvabione (isolated from balsam fir tree, *Abies balsamea* L.) both have JHA activity against various insects (Dhaliwal and Arora 2003; Dhaliwal et al. 2006).

There are also some other chemicals which block the synthesis of natural JHs, facilitate JH degradation, or destroy corpus allatum in insects (Leighton et al. 1981; Dhaliwal et al. 2006). These chemicals are antiallatotropins, or precocenes and are referred as Anti-Juvenile Hormone Agents (AJHAs) or JH antagonists. Some of the initial examples of AJHAs include precocene-I, prococene-II and precocene-III which were isolated from *Ageratum houstonianum* Mill. and *A. conyzoides* L., respectively. These precocenes are metabolized inside the body of insects into cytotoxic compounds (cytotoxins) which selectively disrupt the functions of corpus allatum, promote precocious metamorphosis, induction of sterilization in female adults, initiation of diapause and impediment of biosynthesis of sex pheromone.

Table 8.1 List of Juvenile hormones and their associated details

Category of JH	(Insect from which it was isolated for the first time	Chemical formula (chemical name)	Chemical structure
JH-0	Tobacco hornmoth, *Manduca sexta* (Judy et al. 1973)	$C_{19}H_{32}O_3$ (methyl (2E,6E)-10R,11S-(oxiranyl)-3,7-diethyl-11-methyl-2,6-tridecadienoate)	
JH-I	♀ Cecropia moth, Hyalophora cecropia (Roller et al. 1969)	$C_{18}H_{30}O_3$ (methyl (2E,6E)-10R,11S-(oxiranyl)-7-ethyl-3,11-dimethyl-2,6-tridecadienoate)	
JH-II	Cecropia moth, *H. cecropia* (Meyer et al. 1968)	$C_{17}H_{28}O_3$ (methyl (2E,6E)-10R,11S-(oxiranyl)-3,7,11-trimethyl-2,6-tridecadienoate)	
JH-III	Tobacco hornmoth, *Manduca sexta* (Bowers et al. 1965; Judy et al. 1973)	$C_{16}H_{26}O_3$ (methyl (2E,6E)-10R-(oxiranyl)-3,7,11-trimethyl-2,6-dodecadienoate)	
JH-B3	Drosophila spp. (Richard and Gilbert 1991)	$C_{16}H_{26}O_4$ (methyl (2E,6E)-6S,7S,10R-(dioxiranyl)-3,7,11-trimethyl-2-dodecaenoate)	
Methyl farnesoate	Insects and crustacians Nagaraju (2007)	$C_{16}H_{26}O_2$ (methyl (2E,6E)-3,7,11-trimethyl-2,6,10-dodecatrienoate)	

Later, some new compound with like compactions (vertebrate hypocholesterolemic agents), fluoromevalonate (vertebrate hypocholesterolemic agents), Piperonyl butoxide (PBO), imidazole, acetylenic compounds, cyclopropyl amines, furanyl compounds, ETB (ethyl 4-(2- pivaloyloxybutyloxy)-benzoate) and EMD act as JH-receptor antagonists and AJHAs (Staal 1986; Dhaliwal et al. 2006).

8.3. Insect communication based approaches

In an environment surrounding insect's population, different kinds of olfactory, gustatory, visual, auditory or/and tactile stimuli are present. Such stimuli modify the insect's behavior partially or completely. Insects respond to these stimuli detecting them by the chemo- or mechano-receptors present on different parts/organs of insect's body. However, fundamental and crucial mode of communication is chemical signaling/messaging. Insect's communication may be interspecific (communication between two different species) or intraspecific (communication between two same species). Such types of communications elicit various behavioral changes and are accomplished by sending various communicational signals like stridulatory-noise, flashing-light, chemical-cues etc. The purposes of these communication signals are: i) communicate one's presence; ii) defense, deception or camouflage; iii) locate the host-plants by pests and prey or host by entomophagous insects; iv) establish territoriality; v) locate and recognize sexmates, nestmates or kins; vi) facilitate courtship, copulating and mating; vii) panic the invader; viii) warning the population of danger; ix) regulate ecological behavior of insects like migration, trivial movements, dispersal, aggregation etc.; x) provide clues for exact location of food and other sources. These purposes are achieved using five sensory modalities including contact or tactile senses (taste and touch) and remote senses (vision, olfaction and hearing) (Dhaliwal and Arora 2003; Dhaliwal et al. 2006). .

Tactile communication is used in the insects with poor sound perception and vision. Antennal tapping by male blister beetle [*Mylabris* and *Lytta* species (Coleoptera: Meloidae)] on all sides of body of female blister beetle stimulate her for courtship and mating. Dance language of honey bees inside the colony in form of "Round Dance" (a series of circular turns with recurrent changes in direction) and "Waggle Dance" (a series of abdominal waggles on a straight run after each half-circle turn on pattern of figure eight) is also types of tactile communication to signal the other nestmates about distance, location and quality of food source. Tactile signals are generated by whirligig beetles [*Gyrinus* species (Coleoptera: Gyrinidae)] in form of ripples to keep away the members of same species and detect the presence of any predator or prey in its vicinity. Vibrations generated in the host-plant tissues by treehoppers (Hemiptera: Membracidae) are tactile mode of communication to elicit alarming or protective-maternal behavior (Meyer 2006).

Acoustic communication is very well developed in some insects especially in orthopteran which have well developed stridulatory and auditory organs on abdomen (grasshoppers) and tibia (crickets). The sounds generated by these organs or by different ways in various insects may be a mating call for opposite sex and alarming call for other individuals or invaders (Meyer 2006).

Visual communication involves the clues stimulated from colored patters, body moments and light-flashes in different insects. For examples, colored patterns in adults and larvae of butterflies and moths are used to scare away the natural enemies; whereas, light-flashes in fireflies serve as mating communication between opposite sexes. For examples, males of *Photinus consumilis* generate 3-5 short flashes, while in response, females produce double flash (Meyer 2006).

Chemical communication is major mode of inter- or intra-specific dialogue in insects. Insects are more momentously dependent on chemical communication than other modes of communication. The chemicals involved in inter- or intra-specific communication are termed as "Semiochemicals" or "infochemicals" which have been and still are being targeted for the development of biorational insecticides that are exploited in sustainable management of insect pests of various economical crops) (Dhaliwal and Arora 2003; Meyer 2006).

8.3.1. Semiochemicals: concepts and categories

The word "semiochemical" is a combination of two words i.e. semio and chemicals which have been derived from a Greek world "semeon" referring to sign or signal and chemical, respectively. Some scientists have deployed semiochemicals as infochemicals because these convey only information between two same or different organisms. These semiochemicals may be of natural origin including various parts of plants (flowers, leaves, roots or stem barks), microbial secretions, insects' glands, excretory products, reproductive organs etc., non-living origin (apneumones) or of synthetic nature. Semiochemicals elicit coded or decoded chemical messages which may be advantageous for emitter, receiver or both. The chemical messages evoked by semiochemicals stimulate two types of changes in reciever's behavior i.e., short-term and reversible behavioral change in response (releaser effect) or long-term irreversible physiological and/or biochemical change in response (primer effects). The most important of short-term and reversible behavioral responses include aggregation, attraction and repellence elicitation (Pedigo 2003; Chapman 2003).

The study of semiochemicals is a part of chemical ecology of any organism. Semiochemical is a chemical or mixture of chemicals that elicit some behavioral responses in form of chemical messages/communications between two same (intarspecific) or two different species (interspecific) for accomplishment of various aims including finding mates, food and habitate resources, cautioning natural enemies, avoiding competition (Ayasse 2010). They are classified into two major groups intraspecific semiochemicals (pheromones) and interspecific semiochemicals (allelochemicals). The interspecific semiochemicals (allelochemicals are further classified into allomones, kairomones, synomones, apneumones and antimones (Cork 2004; Dhaliwal et al. 2006) (Fig. 8.2).

8.3.1.1. Pheromones

The word pheromone originates from two Greek words "*phero* or *pherein*" means "to bear or transport" and "*hormone*" means "impetus or stimulate" and introduced by Peter Karlson and Martin Luscher in 1959. Pheromones are also called ectohormones and "*Bombykol*" was first most of such ectohormone which was isolated and characterized from female *Bombyx mori* by Adolf Butenandt. Pheromones are those intraspecific chemical factors which are excreted out of the body of emitters and trigger social responses in receivers of same species. Pheromones are categorized into following two general classes on the basis of their mode of action or responses stimulated (Matthews and Matthews 1979; Jutsum and Gordon 1989).

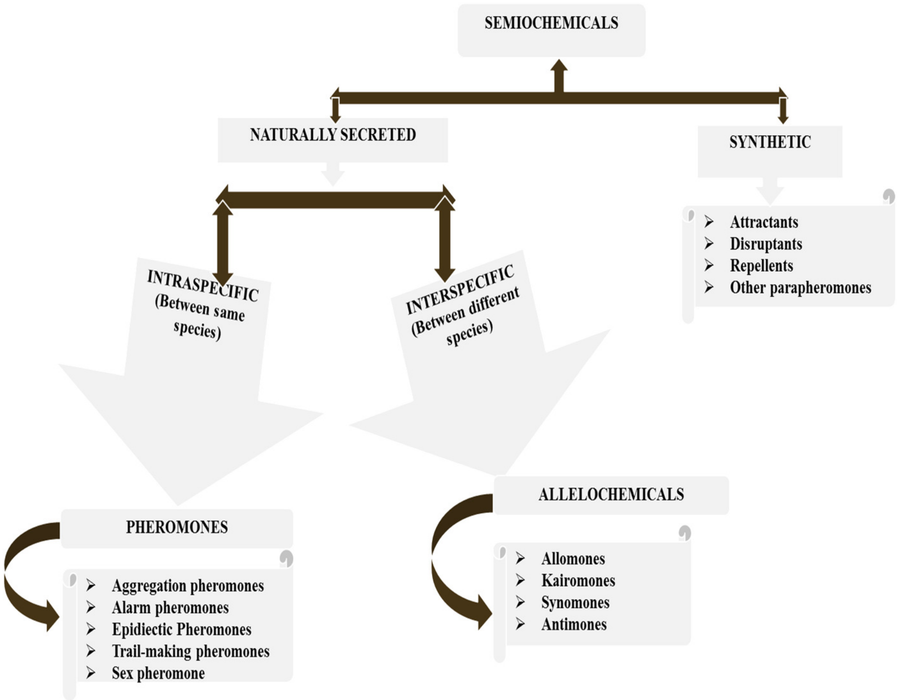


Fig. 8.2 Schematic diagram of the categories of semiochemicals (Dhaliwal and Arora 2003; Dhaliwal et al. 2006)

i) Pheromones exhibiting primer effects (Primer Pheromones)

These pheromones trigger off a series of physiological changes in the receiver without stimulating any immediate change in its behavior. The physiological changes triggered by these pheromones are not reversible. They provoke responses in the receivers through gustatory sensilla. The best known examples of such pheromones are produced by social insects like ants, bees, wasps, termites. Such pheromones stimulate gustation, mediate reproduction and regulate caste determination in these insects. The practical importance of such pheromones in IPM program is negligible and insignificant (Pedigo 2003; Cork 2004).

ii) Pheromones exhibiting releaser effects (Releaser Pheromones)

These pheromones induce instantaneous and reversible change in the behavior of the receiver. Such pheromones are characteristically odorous, redolent and evocative. They stimulate behavior communications and responses in the receivers through olfactory sensilla and act directly on the central nervous system of receiver. They are used as potential and successful biomolecules in pest management program due to their practical importance in IPM program of insect pests. On the basis of variety of behavior modification induced by pheromonal communication, releaser pheromones are further classified as sex pheromones, alarm pheromones, epideictic pheromones, trail pheromones and aggregation pheromones (Jutsum and Gordon 1989; Cork 2004).

Sex pheromones

Sex pheromones are those intraspecific semiochemicals which are mostly secreted by females of a species to attract males of the same species for mating. However, in *Bicyclus anynana*, male butterflies produce sex pheromones to trigger courtship responses in female butterflies (Nieberding et al. 2008). Such pheromones are mainly emitted by Lepidoptera, Diptera species. Sex pheromones may be monocomponent pheromones (composed of one chemical compound) or multicomponent pheromones (composed of more than one chemical compounds in specific ratio). The species specificity to sex pheromone is due to variation in the ratio of different chemical compounds in multicomponent pheromones though these chemical compounds have same chemical nature for two or more different insect species (Table 8.3).

Aggregation pheromones

Aggregation pheromones are intraspecific semiochemicals which are released by one gender of a species to attract both sexes of the same species for exploiting a specific resource like food, appropriate mating or hiding site, etc. These are mainly emitted by Coleopterous species (Heuskin et al. 2011).

Alarm pheromones

Alarm pheromones are intraspecific semiochemicals which make the conspecifics vigilant and trigger behavioral change or response in conspecific population to get dispersed. Such types of pheromones are conspecific features of social or gregarious insects and some insect pests belonging to Aphididae and Thripidae. Alarm pheromones have great potential in IPM program of many insect pests of economical crops, fruits, vegetables, ornamentals etc., (Verheggen et al. 2010).

Trail pheromones

Trail pheromones are mostly secreted by workers members of social insects. The worker cast of the colonies of social insects drop these pheromones inform of trail which indicate the track to be followed by the scout insects for locating food resource. These kinds of pheromones are typical characteristic of ants and termites (Tschinkel and Close 1973).

Host-marking pheromones

Host marking pheromones are those intraspecific semiochemicals which are secreted to diminish intraspecific competition for oviposition, space etc. Host-marking pheromones are mostly secreted by female parasitoids for marking the host (Heuskin et al. 2011).

8.3.1.2. Allelochemicals

Allelochemicals are interspecific semiochemicals which elicit chemical-signals based communication in some members of different species. Allelochemicals include repellent, attractants, antifeedants and a gigantic group of other compounds/molecules that regulate interspecific behaviors. Herbivory evolved on the basis of two types of interactions between plants and herbivores. These interaction may be mutualistic or/and antagonistic. The existence of antagonism between plants and herbivores is justifies when host plants fed on by herbivores try to repel or kill herbivore by some endogenic obnoxious, noxious and lethal phytochemicals. These phytochemicals induce antixenotic (antifeedant, repellent, anti-oviposition and adverse behavioral effects) and antibiotic (adverse effects on growth, development, survival) effects in insects. They constitute a variety of plant secondary metabolites like unusual aminoacids, sugars, alkaloids, terpenoids, flavonoids, polyacetylenes etc. (Dhaliwal et al. 2006). These allelochemicals may be of plant origin (botanicals, phytpalaxins, allomones etc.) and animal origin. The allelochemicals produced by natural enemies like predators, parasitoids, pathogens have also significant importance in pest management programs. For example, delta-endotoxin produced by *Bacillus thuringiensis* possesses lethal toxicity against many lepidopterous and coleopterous insects (Dhaliwal and Arora 2003).

Allomones

Allomone originates from two Greek words "*Allos*" and "*Horman*" which refer to "other" and "to excite", respectively. Allomones include those interspecific message-bearing chemicals (semiochemicals) which mediate chemical communication between emitter and receiver specifically providing adaptive advantages and recompenses to the emitter. Repellents, antifeedants, oviposition deterrents etc. are considered Allomones. For examples, Chemical emitted from Caterpillars of *Lycaena arion* act as an allomone because this chemical invites ants and triggers caring-giving behavior in them. The ants carry the caterpillar among their broods inside nest where caterpillar starts feeding on the larvae of ants (Pierce and Elgar 1985).

Kairomones

Kairomone is derived from two Greek words "*Kairos*" and "*Horman*" which mean "opportunistic" and "to excite", respectively. Kairomones include those interspecific semiochemicals which stimulate chemical communication between emitter and receiver specifically providing adaptive benefits to the receiver. Attractants emitted from host plants for phytophagous insect pests, attractants emitted from host/prey or their products for entomophagous insects, aggregation stimulants etc. are referred to kairomones. For examples, the odor emitted from its host is a kairomone which benefits its parasitoid *Euclytia flavahe* (a parasitic fly) (Aldrich and Zhang 2002).

Synomones

Synomone is a derivative of two Greek words "*Syn*" and "*Horman*" which mean "with" and "to excite", respectively. Synomones include those interspecific semiochemicals which trigger chemical communication between emitter and receiver specifically providing adaptive benefits to both the emitter and receiver.

Attractants emitted from plants parts, especially reproductive parts for pollinators as well as from pest-infested plants for entomophagous insects (predators and parasitoids) are referred to synomones. Defensive allelochemicals emitted from plants due to feeding of caterpillars act as synomones because these compounds attract the parasitoids which parasitize these caterpillars and save the host plants from herbivory (Dhaliwal and Arora 2003; Dhaliwal et al. 2006).

On the basis of chemical nature of biomolecules possessing semiochemical properties, semiochemicals are classified into twenty four categories. These categories include esters (carboxylic (430 esters), acetate (340 esters) and cyclic esters (75 esters), hydrocarbons (580 types), ketones (400 types), alcohols (primary (210 alcohols), secondary (150 alcohols) and tertiary alcohols (30 alcohols)), amines (300 types), aldehydes (260 types), carboxylic acids (210 types), epoxide (100 types), phenols (55 types), spiroacetals (50 types), diols (40 types), quinones (40 types), dioxy (30 types), sulfur compounds (30 types), ethers (20 types), furans (20 types), polyhydroxy (20 types), pyrans (15 types), triols (5 types) and oximes (5 types) (El-Sayed 2016).

Semiochemicals based biorational bioagents or biomolecules disrupt the feeding, mating or oviposition behavior of insects and have strong edge on the conventional insecticides in crop pest management program. Depending on the type and nature of semiochemicals, detection and monitoring of pest population, mating disruption, attract-trap-kill by annihilation or confusing strategy and push-and-pull, attraction of biocontrol agents (predators and parasites) are the practical roles of semiochemicals which can be utilized for effective, ecofriendly and economical IPM program of insect pests of various crops (Brown 2008; Heuskin 2009; Verheggen et al. 2010). The utilization of semiochemicals is preferred over synthetic insecticides because former have adverse effects on pests but no toxic effects on non-target oganisms, possess least mammalian toxicity, are nonpersistent and environment-friendly, required in less quantity (low dose rate) and demonstrate slow rate of resistance developments in insects.

8.3.2. Insect pheromones: Implementation and potentials in IPM

Insect pheromones are those semiochemicals which are produced inside their body by special glands, then are released from their body, pass through air or water and are detected by the receiver (other insects of same species) with the help of different sensilla (Raina et al. 2003). Insect’s pheromones elicit different types of behavioral or physiological changes in the receivers depending on the type of the pheromone. Chemical signals emitted from insect’s pheromones may be short-term (e.g., pheromones used for cautioning danger or stimulating mating/reporducion) or long-lasting term (e.g., pheromones used for specifying territorial boundaries and marking food sources). These pheromones consist of a range of hydrophobic to hydrophilic peptides including long-chain saturated esters, aldehydes and alcohols. More than 1600 insect’s pheromones have been isolated and identified from more than 1500 insect species (Arn et al. 1992; Islam 2012). Most commonly used pheromones in insect pest management program are sex pheromones which are most commonly released by females with some exceptions in insects where males release sex pheromones (e.g. cotton boll weevil, *Anthonomas grandis;* cabbage looper, *Trichoplusia ni* and Mediterranean fruit fly, *Ceratitis capitata*). But the sex pheromones released by females attract opposite sex at longer distance, more strongly excite opposite sex to copulate and are more important in IPM than sex pheromones released by males in insects. The major insect's orders producing sex pheromones include Dictyoptera, Orthoptera, Hemiptera, Mecoptera, Coleoptera, Neuroptera, Lepidoptera, Diptera and Hymenoptera. Sex pheromones are synthesized from fatty acids (alcohols, aldehydes and acetates based pheromones are produced) or from linoleic acid or linolenic acid (straight-chain carbohydrates based pheromones are produced) obtained from plants during feeding (Landolt 1997; Chapman 2003).

Pheromones as behavior modifiers play a pivotal role in insect pest management program. The discovery of bombykol (sex pheromone of *Bombyx mori*) in 1959 by Adolf Butenandt motivated the scientists to explore and exploit the pheromones in IPM program of various insect pests of economic importance. Thousands of pheromones, parapheromones or pheromone mimics have been investigated, formulated and used against insect pest of economical crops (Table 8.3). They are used for detecting, monitoring, forecasting and control of insect pests' population using different techniques like mating-disruption or confusing/decoy technique, Monitoring technique, Mass-trapping technique and Attract-and-Kill technique (Horowitz and Ishaaya 2004; Witzgall et al. 2010).

8.3.2.1. Mating-disruption or confusing/decoy technique

In this technique, lures which are developed from synthetically produced pheromones are used. These lures are blend of major along with some minor chemical components that mimic the excitatory effects of the pheromone naturally produced by insects. This technique involves the introduction of multi-sources of sex pheromone in an ecosystem for making the male population confused and restraining their capability to trace calling-females. The lures or synthetically produced pheromones mask the natural pheromone plume released by female population; limit the ability of males to retort the calling-females in the ecosystem and divert the males to follow pseudo-pheromone-trails to trace the mates (Fig. 8.3). These phenomena either delay or prevent the mating process. Delay in mating imposes consequent negative impact on fertility and results in depositing fewer numbers of fertilized eggs by females during her life time; whereas, complete inhibition in mating devoid the females from depositing fertilized eggs, as the eggs get reabsorbed inside their reproductive system. In both cased, the population of the target insect pest is consequently reduced and losses are avoided (Murray and Alston 2010).

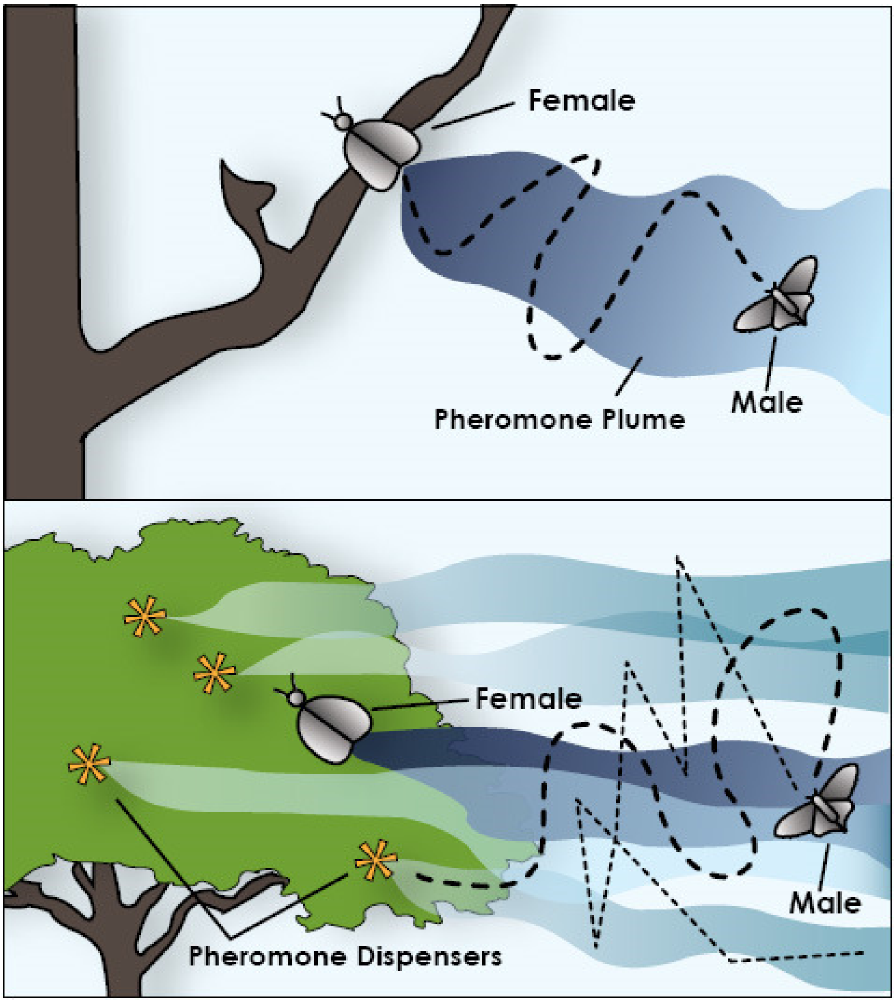


Fig. 8.3 A) Ecosystem without lure indicating normal male following the true trail and locating female for mating. B) Ecosystem with lure dispensers releasing synthetic pheromone volatiles which are masking the natural pheromone released by female, confusing the normal male to locate and respond the calling-female and diverting the male to follow pseudo-pheromone-trails. The confused male, if fly less randomly (following the thick dotted line), may settle on pheromone trap/dispenser or may fly down near female but mating will be delayed. The confused male, if fly arbitrarily (following the thin dotted line), will remain betrayed, never locate the female and mating will be prevented. (Reproduced with permission by: Utah State University, http://utahpests.usu.edu/IPM/images/uploads/factsheet/codling-moth-md/fig-1-mating-disruption.jpg).

The success of this technique depends on following considerations and factors (Cocco et al. 2013):

1) Determine the suitability of the field, crop or orchard for the implementation of mating-disruption technique. Square and rectangle field are the most suitable blocks whereas, long, narrow sites, few furrows and small backyard planting are inappropriate sites for this technique.
2) Planning area-wide and season-long/year-long monitoring programs
3) Implementation of mating-disruption technique on large area
4) Ecosystem harboring very high population of insect pests is absolutely wrong site whereas; ecosystem having low to moderate insect pest population is an appropriate site for the implementation mating-disruption technique. Very high insect pest population does not reduce rather sustains the chances of mating despite the implantation of sex pheromone.
5) This technique should be used in integration with other IPM components

8.3.2.2. Monitoring and pest-scouting technique

Monitoring and pest-scouting are the crucial components of any successful IPM program and make the foundation of pest management decisions. The application of pheromones is concerned with the detection pest incidence and monitoring population fluctuation during cropping season. After implementing pheromone traps, this technique helps in detecting both the occurrence and density of insect pest species in an agroecosystem. Monitoring the traps on regular basis also helps to estimate insect pest population, determine new hotspot at very early stage of the crop, define threshold, forecast the chance of outbreak of key pest species and track the incidence of any invasive insect species. Monitoring using pheromones is an important method for detecting quarantine insect pests like fruit flies (Dhaliwal et al. 2006).

8.3.2.3. Mass-trapping technique

In this technique, pheromones are employed in/on the traps having sticky surfaces or filled with any liquid (water, kerosene oil, alcohol etc.) to trap or catch the attracted insects. The shape, size, color, density, height and position of pheromone traps are the key factors which determine the successful results of the traps. Shape, size, color, height and position of pheromone traps vary depending upon the target insect species and crop and its stage; whereas density of traps per unit area depends on the area and economic importance of crop, geographical area and density of pest population. This technique is highly restricted to an ecosystem where chemical control with insecticides is either ineffective or intolerable due to environmental degradation (Pedigo 2003; Dhaliwal et al. 2006).

8.3.2.4. Attract-and-Kill technique

This technique is modified form of mass-trapping. In this technique, pheromone is coadministrated with any killing agent more specifically any odorless insecticides. The pheromone attracts the insect species while insecticide kills the attracted insect species by contact action. The mixed in insecticide enhance the attract-and-killing potency of the pheromone trap and overcome the issue of low trapping efficiency of pheromone traps. This technique is also termed as Male-Annihilation-Technique (MAT) when male attracting pheromone is used in trap. This technique is widely used to control fruit flies (Pedigo 2003; Dhaliwal et al. 2006).

8.3.2.5. Pheromone Nanogel Technique

With advent of nanotechnology, pheromone application technique has also been modified and improved. Low molecular mass gelator has been used to prepare a nanogel from methyl euginol (sex pheromone for fruit flies). This pheromone nanogel (nano-gelled pheromone) is highly stable at open conditions, slows down the volatilization of the pheromone evocatively and significantly, facilitates the handling and carriage of pheromone without preservation by refrigerator chilling and reduces the intensity of refreshing or recharging the pheromone in the field. This technique has transformed the conventional pheromone application technique (pheromone traps) into a simple, practical and low-cost approach having satisfactory safety profile, long-lasting residual activity, extraordinary efficacy and significant potential for crop protection (Bhagat et al. 2013)

8.3.2.6. Phromone dispensing technology

In this technique different kind of dispensers made up of materials which slow down the release of pheromone and enhance the shelf-life of the molecules. Different kind of pheromone dispensing techniques have been developed and used for the control of various insect pests especially fruit flies. For example SPLAT (Specialized Pheromone and Lure Application Technology) has been developed by ISCA Technologies, Inc., Chicago Ave, Suite C2 Riverside for the management of fruit flies. This technique has multiple application methods, is easy to apply on large and small area, ensure application of same quantity of pheromone, is rain-resistant, ensure the efficacy upto six months and can be mixed with kairomones or feeding stimulant. Isomate-CM/OFM TT dispenser (a "twin tube" assembly of two "ties" containing 423.6 mg of a multicomponent pheromone blend) implemented at a rate of 500 ties per ha (200 per acre); Checkmate dispensers (CM-OFM Duel membranes, a double packet of pheromone-loaded pads behind controlled-release membranes) installed at a rate of 500 ties per ha (200 per acre) and Checkmate Puffer pheromone dispensers (a plastic cabinet enclosing an aerosol canister containing the pheromone blends) deployed at a rate of 1 per acre all three in the upper one-third of the tree canopies suppressed adult catches of oriental fruit moth (OFM), *Grapholita molesta,* codling moth (CM), *Cydia pomonella* and lesser appleworm, *Grapholita prunivora* to near-zero levels for the entire season (Agnello and Reissig 2007; Murray and Alston 2010) (Fig. 8.4).

Isomate-CM/OFM TT (twin tube) dispenser

Checkmate CM-OFM Duel-membrane dispenser

Suterra CM/OFM Puffer

Fig. 8.4 Display of different pheromone dispensing technologies (Reproduced with permission by Utah State University Extension IPM Program, and uploaded of website: https://www.google.com.pk/search?biw=1366&bih=624&noj=1&tbm=isch&oq)

8.3.2.7. Microencapsulated pheromone technology

Microencapsulation is an advanced technology and is used to develop microencapsulated formulations of pheromones by interfacial polymerization. Small droplets of the pheromones are enclosed inside the polymer capsules which are small enough to be applied as suspension and regulate the pheromone release rate. Microencapsulated formulations of pheromones are easy to apply on large scale with conventional spray equipment, cause high levels of communication disruption of insects, are compatible with other chemical products (insecticides and fertilizers) in most of the tank spray system, ensure best coverage of the crop/tree with pheromone, have prolonged residual activity (days to weeks depending on climatic condition, capsule size as well as chemistry and properties of pheromone) and are convenient for integration with insecticide-based IPM program to reduce pest pressure. Microencapsulated pheromone technique has been reported to suppress oriental fruit moth (Il'Ichev et al. 2006) and codling moth (Stelinski et al. 2005) effectively by disrupting mating response. CheckMate® Flowable is a product developed by Suterra® that consists of micro-encapsulated pheromone formulated for mating disruption in oriental fruit moths (CheckMate® OFM-F) and codling moth (CheckMate® CM-F) (Agnello and Reissig 2007; Murray and Alston 2010). Bohnenblust et al. (2011) evaluated three sex pheromone MD technologies (CM and OFM Disrupt Micro-Flakes, Isomate CM/OFM TT, and both a CideTrak OFM and a CideTrak CM dispenser containing both codlemone and pear ester), and four dispenser densities (250, 375, 425, and 500 dispensers ha^{-1}) for the management of the codling moth (CM), *Cydia pomonella* (L.), and the oriental fruit moth (OFM), *Grapholita molesta* (Busck) (both Lepidoptera: Tortricidae), in Pennsylvania apple orchards. They reported that CideTrak CM/pear ester combination and Isomate CM/OFM TT treatments both significantly minimized CM captures in traps in 2007 and 2008. Meanwhile, OFM trap shutdown was highest in the CheckMate Duel densities of 375 ($99.9 \pm 0.08\%$) and 500 dispensers ha^{-1} ($98.9 \pm 0.07\%$) and the Isomate CM/OFM TT treatment ($98.0 \pm 1.13\%$), and lowest in the 250 dispensers ha^{-1} density treatment ($94.3 \pm 3.23\%$).

8.3.2.8. Potential of pheromones in IPM

Use of pheromone based management system has an edge over conventional insect control program which comprises of insecticide spray. The former is safe for non-target organisms, highly species specific, selective, specifically targets the reproductive stages of insect life and prevents the production of most voracious and damaging stages. However, the later targets the damaging stages of insect life, is nonselective and toxic for non-target organisms. Pheromones in form of different techniques and technologies have important position in IPM program as they are highly target specific, ecofriendly and economical, require very low doses, are safe for natural enemies and compatible with other components of IPM program. However, ever, parapheromones or synthetic pheromones are available in the markets only for few insect species. A regular and routinely recharging or replacement of pheromone lures required for good and reasonable trapping of insects otherwise efficacy of the lures deteriorate with the passage of time and insect catching is reduced. An agroecosystem harboring insect pest complex cannot be protected from damage by pheromone management system because pheromone is species specific and captures as well suppresses on one insect species not all.

Pheromone based management system, technologies or devices playing their vital role in controlling variety of insect pests of economic crops, fruits, vegetables, ornamentals, vineyards fiber and fodder crops and pastures. The most important and historical success stories involving exploitation of pheromone based management system include the significant suppression of codling moth (> 80% reduction in moth-catches/trap) and reduction in fruit losses (0.1-1% fruit damage) as well as in insecticide application (> 75% reduction) in pear, apple, pomegranate and walnut in California, Pacific Northwest, Sacramento valley, Lake County and Randal Island region. The capturing and suppressing of codling moth population in fruit orchards in many countries of the world is accomplished by using different types of pheromone dispensers (Hand-applied dispenser, Hollow-fiber dispensers, High-emission dispensers etc.), microencapsulated pheromones, pheromone traps, nanogelled pheromones and MAT-devices (Ahmed 2014). Hollow-fiber pheromone dispensers were used for mating disruption in IPM program of tomato pinworm (*Keiferia lycopersicella*) in 1970s and 1980s in Mexico successfully causing 30-35% reduction in fruit damage (Trumble 1997). A successful mating disruption program was deployed during 1980s in Coachella Valley, USA and many European countries against pink bollworm (*Pectinophora gossypiella*) on cotton using hollow-fiber, twisted-tie-rope, laminate-flake, microencapsulated-pheromone or laminated-membrane dispensers that caused 80-100% reduction in pesticide application against pink bollworm (Ahmed 2014). Mating disruption program using membrane, laminate and rope dispensers (hand-applied dispenserks), puff-type dispensers and microencapsulated formulations has been carried out successfully for oriental fruit moth in many countries (Pickel et al. 2002). For example, 0-3% damage was reported in peach orchards in California when hand-applied pheromone dispensers were deployed for mating disruption of oriental fruit moth. Manipulation of different types of pheromone traps (delta, funnel or water trapes) in IPM program (integrated with insecticides) of *Tuta absoluta* (tomato leafminer) demonstrated losses much below ETL (1-5%) in Egypt (Taha et al. 2013) and significant results against this notorious pest in Spain and Argentina (Botto 1999).

8.3.3. Plant-produced allelochemicals: Perspectives and potentials in IPM

In plants, two types of metabolites are produced as a result of metabolic processes. Primary metabolic processes in plant system produce primary metabolites (enzymes, hormones, carbohydrates, lipids, proteins and phosphorous compounds) from inorganic compounds for the growth and reproduction of plants. Some of these plant's primary metabolites act as nutrients, feeding stimulants and toxicants. As a result of secondary metabolites in plant system, secondary metabolites are produced that are considered to play important role in plant defense against herbivore feeding. Such types of plant metabolites illicit a chemical based communication between plants and insects and are called allelochemicals. These allelochemicals have antixenotic and antibiotic effects and play vital role in triggering resistance in plants against herbivores (Dhadialla and Bhathal 1994; Pedigo 2003). Plant produced allelochemicals (Table 8.2) illicit intrinsic as well as extrinsic defense against herbivores. They may act as kairomones, allomones, synomones or alternatively (Price et al. 1980; Ahmad et al. 2004) depending on the nature of their effects on responding organism. An allelochemical, at the same time, may act as all aforementioned categories. For examples, terpenoids produced by pine tree as secondary metabolites not only act as allomones for phytophagous insects (herbivores) but also act as chemical cue for bark beetles eliciting kairomonic effects and help in searching their food source (bark of pine). Same terpenoids of pine trees also act as synomone when they attract predators of bark beetles (Nordlund 1981; Pasteel 1982). Different food bodies like nectors, pollens etc., plant volatiles and scents emitted from floral parts or glands act as synomones for predators, parasites and pollinators (Leius 1967; Smiley 1978; Read et al. 1970; Vinson 1984; Pellmyr and Thien 1986). The pine needles attacked by aphids volatilized a chemical odor which attract and help coccinellid predators to search their prey (aphids) (Kesten 1969). Flint (1979) has reported that cotton leaves damaged by insect pests especially by Lepidopterous pests produce a terpenoid (caryophyllene) that attract *Chrysoperla carnea* towards plants. The pants damaged by herbivores emit mixture of behavior-modifying volatile organic compounds which are called as herbivore-induced plant volatiles (HIPVs) (Mumm and Dicke 2010). Such HIPVs mainly consists of terpenes (monoterpenes, sesquiterpenes, homoterpenes), aromatic compound and green-leaf volatiles (C6 aldehydes, alcohols, and acetates) (Pichersky et al. 2006) which act as chemical cues to indicate the presence of potential host/prey and help their natural enemies to trace their prey/host (Verkerk 2004). A mixture of volatiles emitted from *Phaseolus lunatus* L. (lima bean plants) due to feeding of *Tetranychus urticae* Koch (two spotted spider mite) appeals the *Phytoseiulus persimilis* Athias-Henriot (predatory mite) (Dicke and Sabelis 1988; Du et al. 1998). As a result of pea aphid (*Acyrthosiphon pisum* (Harris) infestation on beans (*Vicia faba* L.), beans plant emit HIPVs which attract aphid parasitoids (*Aphidius ervi* Haliday). Stimulation of volatiles emission from the host plant *Ulmus minor* Mill. is triggered by the oviposition initiation of elm leaf beetle (*Xanthogaleruca luteola*) on its host plant. Then the emitted volatiles attract the egg parasitoid (*Oomyzus gallerucae* Fonscolombe) of elm leaf beetle (Meiners and Hilker 1997, 2000). The plant produced allelochemicals ingested by the phytophagous insects are cycled inside their bodies and then the biomolecules produced as byproducts act as kairomones for chemical communication between insects and its natural enemies (Vinson 1984). For examples, corm attacked by *Heliothis zea* (corn earworm) produces trichosane which is ingested by *H. zea* and then derived unchanged to its eggs where this chemical act as kairomone for *Trichograma evanescens* (egg parasitoid) and help the parasitoid in locating the eggs of its host (*H. zea*) (Lewis et al. 1972). Allyl-isothiocyanate released from cruciferous plants helps the aphid parasitoid (*Diaeretiella rapae*) in searching its host (aphid) (Dhaliwal and Arora 2003). A large quantity of terpenoids is volatilized from the corn seedling attacked by armyworm (*Spodoptera exigua*) which attract females of *Apanteles marginiventris* (larval parasitoid wasp) and enhance parasitism (Dhaliwal and Arora 2003).

Monteith (1960) concluded that sometimes, secondary metabolites (allelochemicals) produced by one plant species retard the host/prey searching ability of natural enemies by masking chemical attractants produced either by other plant species or emitted from the body of host/prey after cycling the plant metabolite in its body. For example, odorous chemical emitted from larch and larch sawfly (*Pristiphora erichsonii*) as secondary metabolite (allellochemical) demonstrates 80-90% parasitism of larch sawfly by its tachnid parasitoid in pure larch cultivation but attributes only 10-12% parasitism in mix cultivation because of masking effects of other allelochemicals emitted by other accompanying larch sawfly host-trees in mix cultivation. The allomones based plant defense system against herbivory also repel the natural enemies. For example, Methy Ketone, 2- tridecanon emitted from tomato not only repels herbivores but also deters the natural enemies (Williams et al. 1980; Dimock and Kennedy 1983). Similarly, volatiles released from glandular trichomes of plants deter coccinellids and chrysopid larvae (Belcher and Thurston 1982). Hydroxamic acid produced in graminaceous plant species like wheat maize etc. exhibits antixenotic and antibiotic effects against *Ostrinia nubilalis, Schizaphis graminum, Sitobion avenae* and other insect pests. The rice plant produces pentadecanal which demonstrates allelochemicals effects on various insect pests of rice including *Nilaparvata lugens, Sogatella furcifera, Chilo suppressalis* etc. Tomato foliage divulges antixenotic and antibiotic resistance for *Leptinotarsa decemlineata and Heliothes zea* due to presence of ruten and chlorogenic acid (catecholic amines), α-tomatine (glycoalkaloids), and 2-tridecanone as well as 2-undecanone (methyl-ketones) in tomato leaves (Dhaliwal and Bhathal 1994; Dhaliwal et al. 2006). E-*β*-farnesene (alarming pheromone) is released by potato plant (*Solinum berthaultii*) as allomonic chemical defense against the attack of *Myzus persicae* (aphid). Gossypol (excreted by gossypol glands) emitted from cotton leaves imposes antixenotic and antibiotic effects on various Lepidopterous pests like pink bollworm (*Pectinophora gossypiella*), american bollworm (*Helicoverpa* spp.), armyworm (*Spodoptera* spp.) and (*Trichoplusia ni*) (Dhaliwal and Arora 2003; Dhaliwal et al. 2006).

These plant produced allelochemicals either have allomonic, kairomonic or synomonic effects (Table 8.2). The allelochemicals having allomonic effects can be exploited for repelling or deterring the pest species from feeding, oviposition or sheltering on the crops and ultimately for minimizing the crop losses in an ecofriendly way. The allochemicals having kairomonic effects can be utilized for attracting pest species on trap crops or food baits; thus giving relief to the actual crop. While allelochemicals exhibiting synomonic effects can be exploited in the manipulation of biocontrol agents especially parasitoids facilitating the entomophagous insect in searching its host/prey. Likewise, gene-pole involved in synthesis of allomones and synomones in wild plants, if identified and characterized, can be engineered by modern biotechnological approaches in the cultivated crops and exploited in form of genetically modified crops for ecofriendly pest management program.

Table 8.2 List of plant produced allelochemicals with their target insect and effects

Allelochemicals	Source	Target insects	Effects	References
Allyl-isothiocyanate	cruciferous plants	aphid parasitoid (Diaeretiella rapae)	Synomonic effect	(Dhaliwal and Arora 2003)
Gossypol	Cotton plants	Lepidopterous pests of cotton	antixenotic and antibiotic effects	
E-β-farnesene	potato plant	Myzus; persicae (aphid)	Allomonic effects	
methyl-ketones	Tomato foliage	Leptinotarsa decemlineata and Heliothes zea	Antixenotic and antibiotic resistance	(Dhaliwal and Bhathal 1994; Dhaliwal and Arora 2003)
Catecholic amines	Tomato foliage	Leptinotarsa decemlineata and Heliothes zea	Antixenotic and antibiotic resistance	
Glycoalkaloids	Tomato foliage	Leptinotarsa decemlineata and Heliothes zea	Antixenotic and antibiotic resistance	
Pentadecanal	Rice plant	Various insects pests of rice including Nilaparvata lugens,Sogatella furcifera, Chilo suppressalis etc.	Allelochemicals effects	
Hydroxamic acid	graminaceous plant species	Ostrinia nubilalis, Schizaphis graminum, Sitobion avenae and other insect pests	antixenotic and antibiotic, antifeedant effects	Argandona et al. 1980. 1983; Givovich and Niemeyer 1994; Dhaliwal and Arora 2003
Methy Ketone, 2-tridecanon	emitted from tomato	Herbivores and natural enemies		Williams et al. 1980; Dimock and Kennedy 1983
Caryophyllene (terpenoid)	released by damaged cotton leaves	*Chrysopa carnea* (predator of soft bodied insects and eggs)		Flint et al. 1979
Sinigrin	released by mustard leaves infested with mustard aphids (*Brevicoryne brassicae*)	Attract both mustard aphids (*B. brassicae*) and its parasitoid *(Diaeretiella rapae*)		Read et al. 1970
Trichosane	produced by corn (*Zea mays*)	Trichogramma evanescens (egg parasitoid)		Lewis et al. 1972

8.3.4. Herbivore-produced allelochemicals: Perspectives and potentials in IPM

Phytophagous insects are the component of tritrophic interaction that manages the defense system of plants on one side while tackle the attack of their natural enemies on the other hand. The herbivores cope with the defensive system of plants and defend themselves from attack of natural enemies by producing different kinds of semiochemicals which either suppress or mitigate the plant's defense system or deter the natural enemies directly or indirectly (Dhadialla and Bhathal 1994; Ahmad et al. 2004). The sugar rich honeydew produced by aphids or lycaenid butterfly larvae attracts ants which get food from honeydew and in response protect aphids and lycaenid larvae from predators (Pierce and Mead 1981). The herbivore-produced allelochemicals may act as kairomones detected by their natural enemies. These herbivore's kairomones may be in form of their sex pheromones, (Kennedy 1984), body odor (Noldus and van Lentern 1985), aggregation pheromones (Wood 1982), odor of excretory products (Nordlund and Lewis 1985), odor of eggs (Jones et al. 1973) and body scales (Loke and Ashley 1984). According to Tinbergen (1972), the predatory wasp (*Philanthus triangulum*) of bee locates its prey (bees) by following the chemical clue of odor emitted from the body of bees. The predators of termites search them by following the chemical signals of foraging pheromones emitted by termite's population during foraging (Howse 1984; Ruther et al. 2002). Chemical odor emitted from the body of aphids elicits both the oviposition stimulant and arrestant effects on its predator, syrphid fly (*Syrphus corolla*) while attractant effects on its cecidomyiid predator (*Aphidoletes aphidimyza*) (Dhaliwal and Arora 2003; Dhaliwal et al. 2006). Attraction, retaining and searching behavior of *Apanteles plutella* (endolarval parasitoid) is stimulated by the combination of chemical elicitors produced by its host, *Plutella xylostella* (L.) and emitted by the host plant of Diamond back moth (*P. xylostella*) (Loke et al. 1992; Dhaliwal and Arora 2003). Tricosane sysnthesized and emitted from the scale of *H. zea* attracts *Trichogramma* spp. and enhances the egg parasitism from 13-22% (Jones et al. 1973; Lewis et al. 1975a, b). Hare et al. (1997) reported that exposure of *Aphytis melinus* DeBach (reared in laboratory parasitoid of the California red scale) to O-caffeoyltyrosine (kairomone) before augmentation enhanced the parasitism of *Aonidiella aurantii* (Maskell) (California red scale) by *A. melinus*.

The kairomones emitted by the herbivores also affect plant physiology. Carter (1939) reported fruit abortion and enhanced growth rate; whereas, Bultman and Faeth (1986) documented shedding of buds, fruits, flowers and leaves by plants in response of allelochemicals emitted by herbivores. The allelochemicals having allomonic effects elicit deterrent effects on host plants and their natural enemies. The allelochemicals (allomones) released by gall insects elicit the plants to produce galls as conducive habitat for gall insect. Cardiac glucosides derived from milkweed plant by milkweed butterfly are cycled and then are used as allomones which illicite vomiting in predators of this pest and deter predators from predation (Brown 1969). Similarly, tomatine (alkaloid) derived by corn earworm (*H. zea*) from tomato plants, when cycled in its body, induces negative impacts on the survival, longevity and larval growth of *Hyposter exigua* (larval parasitoid of *H. zea*) inside the body of host (Campbell and Duffey 1981). Ethanol derived by the *Drosophila melanogaster* imposes adverse effects on the survival of its parasitic wasp. Similarly, nicotine when derived by hornworm from *Nicotiana tabacum* in high concentration executes adverse effects on the survival of *Apanteles* spp. inside the body of its host (Gilmore 1938).

8.3.5. Natural enemy-produced allelochemicals: Perspectives and potentials in IPM

Like herbivores, intraspecific communication is triggered in natural enemies by emitted pheromones expecially sex pheromones (Eller et al. 1984; Swedenborg and Jones 1992) which have been assessed for determining various activities and biological parameters of natural enemies including activity of natural enemies in field, assessment of their population density and prediction of parasitism rates in field (Lewis et al. 1971; Morse and Kulman 1985). Aggregation pheromones have potential in manipulation of biocontrol system in IPM. For example, 2-isopropyl-3-methoxypyrazine (aggregation pheromone) produced by conspecies attracts both sexes of *Coccinella septempunctata* adults (Al-Abassi et al. 1998). Combination of pheromones and HIPVs enhances the attraction of natural enemies. A combination of MeSA (HIPVs) and iridodial (aggregation pheromone) proved a stronger attractant for lacewing species (Jones et al. 2011). The semiochemicals released by the natural enemies also play important role in tritrophic interaction because such semiochemicals bring about changing in the behavior and physiology of both the herbivores and plants (Ahmad et al. 2004). The reviewed litreature indicates that predators have evolved such system. Allomones produced and emitted by predators not only attract their prey but also help them to mimic their identity (Ahmad et al. 2004). Predators derive some chemicals from the body of their prey and then exploit these chemicals for mimicking their body odor with that of their prey (Vander-Meer and Wojcik 1982; Ahmad et al. 2004). The synomones released by the predators or parasitoids elicit changes in plants. Predators also produce chemicals having kairomonic properties and when these kairomones are detected by the herbivores (preys), they disperse from the area to sidestep their predation by the invading predators (Dicke and Grostal 2001). Formicid kairomones released by predatory ants elicit behavioral changes in terrestatial ants, bees and wasps (Chadab 1979). Synomones released by the *Pheidole bicoins* (ant species) is a chemical indication of their presence. When presence of these ants is detected through the synomonic cues by *Piper cenocladum* plants, they start to produce food bodies for the predator ants (Risch and Rickson 1981).

8.4. Recent scenario of biorational pest management in Pakistan

In Pakistan, the concept of biorational pest management is mostly theoretical while its practical concept is very limited. The practical use of biorational pest management components on the farmer field is inadequate. Although such approach has great potential in IPM program but they are getting insignificant portion of the pesticide market in Pakistan. Most commonly used biorational products include IGRs and pheromones.

The commercially available, marketed and used IGRs in Pakistan belong to triazine chitin synthesis inhibitors (CSI), Benzoylphenylurea CSI, Juvenile hormone mimics and Moulting hormone agonists. Among triazine CSI, buprofezin [(*Z*)-2-[(1,1-dimethylethyl)imino]tetrahydro-3-(1-methylethyl)-5-phenyl-4*H*-1,3,5-thiadiazin-4-one] (formula: $C_{16}H_{23}N_3OS$) is marketed and being used against variety of insect pests. Buprofezin not only impedes moulting process and demonstrates mortality of nymphs and larvae but also suppresses oviposition by adults and induces sterility in treated insects. This biorational product is found very effective against homopterans, coleopterans and mites in rice, cotton, fruits, vegetables and many other field crops and ornamental plants (Sontakke et al., 2013). Among Benzoylphenylurea CSI group, lufenuron [(*N*-[[[2,5-dichloro-4-(1,1,2,3,3,3-hexafluoropropoxy) phenyl] amino] carbonyl]-2,6-difluorobenzamide)]; ($C_{17}H_8Cl_2F_8N_2O_3$)], triflumuron [(2-chloro-*N*-{[4-(trifluoromethoxy) phenyl] carbamoyl} benzamide); ($C_{15}H_{10}ClF_3N_2O_3$)], diflubenzuron [(*N*-[(4-chlorophenyl) carbamoyl]-2,6-difluorobenzamide); ($C_{14}H_9ClF_2N_2O_2$)], chlorfluazuron [(*N*-[(3,5-dichloro-4-{[3-chloro-5-(trifluoromethyl) pyridin-2-yl]oxy} phenyl) carbamoyl]-2,6-difluorobenzamide); ($C_{20}H_9Cl_3F_5N_3O_3$)] and teflubenzuron [(*N*-[(3,5-dichloro-2,4-difluorophenyl)carbamoyl]-2,6-difluorobenzamide); ($C_{14}H_6Cl_2F_4N_2O_2$) are being used effectively against various insect pests of economic crops. Lufeneuron has been found very effective against various lepidopterous, dipterous and coleopterous pest in various field crops (Gogi et al. 2006; Saeed et al. 2012), vegetables, orchards (Akhtar et al. 2007) and storage structures (Sagheer et al. 2012). Satisfactory suppression of hairy caterpillar, *Euproctis lunata* Walk (Lymantriidae: Lepidoptera) has been achieved by the application of triflumuron and diflubenzuron in nurseries and young plantation (Rahman and Chaudhary 1987). Diflubenzuron and buprofezin explained excellent mortality of the wrigglers and pupae of the mosquito (*Aedes aegypti*) (Jahan et al. 2011). Lufenuron, and triflumuron have been reported as harmless IGRs (clas 1) for beneficial insects fauna especially prasitoids and can be recommended for integrated pest management programs potentially designed for their preservation (Carvalho et al. 2010; Hussain et al. 2010; Sattar et al. 2011). Among IGRs, chlorfluazuron was the most toxic compound (LC_{50} = 0.0006 mg a.i./ml) against *P. xylostella* in Pakistan (Abro et al. 2013). Viper® (Buprofezin) and Match® (Lufenuron) alone and in combination with two insecticides used for seed treatment [Confidor® (Imidacloprid) and Contest® (Thiamethoxam)] at their field recommended dose rate exhibited 80-100% reduction infestation and 65.3-100% larval mortality of *Chilo partellus* Swinhoe (Pyralidae: Lepidoptera) and 80-100% reduction in infestation and 75-100% maggots' mortality of *Atherigona soccata* Rodani (Muscidae: Diptera) upto 15DAT (Arif et al. 2013). IGRs like, lufenuron, triflumuron and buprofezin, demonstrated 96.6, 89.9 and 69.5, mortality of canola aphids as compared to carbosulfan (78.2%), respectively. These IGRs exhibited toxicity against the non-target organisms but lower than synthetic insecticides (Arif et al. 2013).

The most commonly used Juvenile hormone mimics in agroecosystem of Pakistan for plant protection against insect pests include fenoxycarb and pyriproxyfen.

Table 8.3 List of pheromones categories with examples, chemical names and target insects

Categories	Examples	Chemical names	Insects	References
Sex Pheromones	Gyptol	d-10-acetoxy-cis-7-hexadecen-1.ol	Gypsy moth (Perthetria dispar)	(Jacobson et al. 1970)
	Gyplure	d-12-acetoxy-cis-7-hexadecen-1.ol	Gypsy moth (Perthetria dispar)	
	Cuelure	4-[p-(acetyloxy)phenyl]-2-butanone OR 4-(*p*-hydroxyphenyl)-2-butanone acetate	Melon fruit fly (Bactrocera cucurbitae)	(Beroza et al. 1960; Vergas et al. 2000)
	ECB-Lure	Z11- and E11-tetradecenyl acetate (Z11- and E11-14:OAc)	European corn borer (ECB), *Ostrinia nubilalis* (Hubner)	(Ishikawa et al.1999; Linn et al. 2007; Miura et al. 2009)
	Gossyplure	(1:1 mixture of Cis, Cis and Cis, trans isomers of 7,11E-hexadeca-7,11-dien-1-yl acetate)	Pink bollworm, *Pectinophora gossypiella* (Saund.) (Lepidoptera: Gelechiidae)	(Hummel et al. 1973; Golub et al. 1983)
	Litlure	a mixture of cis-9,trans-11-tetradecadienyl acetate (component A) and cis-9,trans-12-tetradecadienyl acetate (component B)	Tobacco cutworm, *Spodoptera litura* (F.)	(Tamaki et al. 1973)
	Spodolure	Mixture of (Z, E), 9,11 Tetradecanyl Acetate and (Z, E) 9,12-Dienyl Acetate (19:1)	Armyworm, Spodoptera litura	(Martinez et al. 1990)
	Looplure	(Z)-7-dodecenyl acetate	Cabbage looper, Trichoplusia ni (Hb.)	(Shorey et al. 1972; Bjostad et al. 1980)
	Heli-lure	Mixture of (Z) 11 Heaxadecanal & (Z) Hexadecanal (97:3)	Red gram pod borer, Helicoverpa. Armigera	
	Trimedlure	mixture of *tert*-butyl (1E,2E,4E)-4-chloro-2-methylcyclohexane-1-carboxylate and *tert*-butyl (1E,2*E*,5*E*)-5-chloro-2-methylcyclohexane-1-carboxylate	Meditarrnian fruifly, *Ceratitis capitapa*	(Valega and Beroza 1967)
	Bombykol	(10*E*,12*Z*)-hexadeca-10,12-dien-1-ol	Silkworm, Bombyx mori	(Butenandt et al. 1959)
	Leucilure	Mixture of (E)-11 hexadecenyl Acetate &	Brinjal Shoot and Fruit Borer *Leucinodes orbonalis*	(Zhu et al. 1987)

Categories	Examples	Chemical names	Insects	References
		(E)-11-Hexadecen-1-o1 (100:1)		
	Nomate-DBM, Checkmate-DBM	(Z)- Heaxadecanal -11-enal & (Z)-hexzadec-11-enyl Acetate OR mixture of (Z)-11-hexadecenal (Z-11-16:Ald) and (Z)-11 hexadecenyl acetate (Z-11-16:Ac)	Diamondback moth (DBM), *Plutella xylostella* (L.) (Lepidoptera:Yponomeu tidae	(Tamaki et al. 1977)
	Methyl eugenol	(4-allyl-1,2-dimethoxybenzene-carboxylate)	Fruit flies, *Bactrocera* Spp.	(Steiner et al. 1970)
	Amlure	(R)-acetoin	Chaffer beetle, *Amphimallon* sp	(Tolasch *et al.* 2003)
	Ferrolure (Ferrugineol")	4-methyl-5-nonanol	*Rhynchophorus ferrugineus* Oliv. (Coleoptera: Curculionidae)	(Hallett et al. 1993)
	Plodilure	blend of four active components, (*Z*,*E*)-9,12-tetradecadienyl acetate (Z9,E12–14:OAc), (*Z*,*E*)-9,12-tetradecadienol (Z9,E12–14:OH), (*Z*)-9-tetradecenyl acetate (Z9–14:OAc) and (*Z*,*E*)-9,12-tetradecadienal (Z9,E12–14:Ald) (100:11:18:12)	Indian meal moth, *Plodia interpunctella* Hübner	(Kuwahara et al. 1971)
Aggregation pheromones	Grandlure	Compounds-I [racemic grandisol, (±)-*cis*-2-isopropenyl-methylcyclobutaneetanol] Compound-II) *cis*-3,3-dimethyl-A1.B-Cyclohexanoneetanol) Compound-III+IV (a 50:50 *cis: trans* mixture of 3,3-dimethyl-A 1 – Cyclohenoacetaldeyde	Cotton boll weevil (*Anthonomus grandis* (Boheman)).	(Tumlinson et al. 1969)
	Sitonlure	4-methyl-3,5-heptanedione	Pea and bean weevil (*Sitonia lineatus* (L.))	(Blight et al. 1987)
	Sitoplure	(R*, S*)-1- ethyl propyl-2-methyl-3-hydroxypentanoate	Stored product weevils (Sitophilus zeamais (L.), Sitophilus granarius (L.) and Sitophilus oryzae (L.))	(Faustini 1982; Phillips 1997)

Categories	Examples	Chemical names	Insects	References
	Lepidolure	Tetradecen-1-ol-acetates(Z9-14:Ac and Z11-14:Ac	Lepidopterans	(Van-der-Kraan and Ebbers 1990)
	Cydlure	(E.E)-8,10-dodocadien-1-ol / dodecan-1-ol / tetradecan-1-ol	Codling moth, *Cydia pomonella* L. (Olethreutidae: Lepidoptera)	(McDonough et al. 1969)
	LBAM-Lure	E11,14:OAc / E9,E11-14:OAc / Z11-14:OAc	Light brown apple moth, *Epiphyas postvittana* (Walker) (Tortricidae: Lepidoptera)	(Bradley et al. 1995)
	Sawfly-Lure	Acetates of pentadecanol / (2S, 3S, 7S)-3,7-dimethyl-2-tridecanol / (2S, 3R, 7R)-3,7-dimethyl-2-tridecanol	Sawflies, Neodiprion serrifer Geoffr. & Diprion pini L. (Hymenoptera: Diprionidae)	(Johansson et al. 2001)
	Tutalure	Mixture of (3E, 8Z, 11Z)-3,8,11-tetradecatrien-l-yl acetate or TDTA (90%) and (3E, 8Z)-3,8-tetradecadien-l-yl acetate or TDDA (10%)	Tomato leafminer or tomato moth, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae)	(Attygalle et al. 1996)

Moulting hormone agonists marketed and used as biorational products in IPM program of various sucking insect pests in Pakistan include methoxyfenozide and tebufenozoid. Priority® (Pyriproxyfen) and methoxyfenozid, alone and in combination with two insecticides used for seed treatment [Confidor® (Imidacloprid) and Contest® (Thiamethoxam)] at its field recommended dose rate exhibited 90.6 and 83.4% mortality of canola aphids as compared to carbosulfan (78.2%), respectively with least toxic effects on non-target organisms (Arif et al. 2013). Buprofezin, pyriproxyfen and diafenthiuron attributed higher reduction in whitefly population that endosulfan, imidacloprid and Thiamethoxam; whereas pyriproxyfen was found safe for parasitoids and predators of whitefly (Naveed et al. 2008).

Semiochemicals especially pheromones are being utilized in IPM program of various crops like cotton, grams, fruits etc. in Pakistan. Use of pheromones for detection and monitoring of pink bollworm (*Pectinophora gossypiella*), American bollworm (*Helicoverpa armigera*) and fruit fly species (*Bactrocera zonata, B. dorsalis, B. cucurbitae*) have been successfully employed in the fields. Shah et al. (2011) reported four specific sex pheromones lures; (10E 12E) – 10, 12 Hexadecadienal for *Earias insulana*, Z11-Hexadecenal Z11 octodecenal (10:2:2) for *Earias vittella*, Z7 Z11 – 16AC (50), Z7 E11 – 16AC (50) Hexadecadienyle Acetate for *Pectinophora gossypiella* and D. Z11-16AL (97), Z9 -16 AL (3) Hexedecenal for *Helicoverpa armigera* for their monitoring in the field. Pheromones are species specific and cannot be used for all fruit flies. Butanone acetate was found very effective for melon fruit fly as BA-trap attracted maximum population of melon fruit flies; whereas methyl euginol (ME) attracted more specimens of other fruit flies like *Bactocera zonata*, *B. dorsalis* and *B. correcta* but no melon fruit fly individual was captured in

ME-trap. Pheromones admixing with odorless insecticides enhance the attract-and-kill potency and periodicity of pheromones and can also be used for management of fruit flies (Gogi et al. 2007).

Table 8.4 List of IGRs categories with their examples, active ingredient, properties, mode of action and target insects

Categories	Major group	Active ingredient (Generic names)	Properties/mode of action/effects	Target insects	References
1) IGRs					
Chitin Synthesis Inhibitor	benzoylureas or benzoylphenylurea (BPUs)	Diflubenzuron Triflumuron Teflubenzuron Hexaflumuron Chlorfluazuron Chlorbenzuron Dichlorbenzuron Flucycloxuron Flufenoxuron Bistrifluron Lufenuron Novaluron Noviflumuron Penfluron Flucycloxuron	Stomach toxicants, sterilants, Ruptured and malformed cuticle, death by starvation. Ovicidal action, reduction in the egg laying rate or hampering the hatching process by impeding embryonic development, alteration in cuticle composition, inhibition of chitin, abnormal endocuticluar deposition that affects cuticular elasticity and firmness, abortive molting, larval and pupal abnormalities (larvae with week and transparent cuticle, splitting of cuticle, small, shrunken, macerated larvae, distorted puparia, pharate pupae and failure of adult eclosion)	Coleopterans, Dipterans, Lepidopterans e.g. cabbage looper (Trichoplusia ni), Spodoptera littoralis, eggs of Helicoverpa armigera and S. litura, Cydia pomonella	(Retnakaran and Wright 1987; Khater 2003, Dhaliwal et al. 2006)
	triazine derivatives	Cyromazine (Larvadex ®, Trigard®)	Growth inhibition, expansion of the body wall abnormal internal growth and development.	Dipetrans, leafminor	(O'Brien and Fahey 1991)
	pyrimidine derivatives	Dicyclanil (ZR ®, ComWin ®),		dipteran	(Bowen et al.1999)
		Buprofezin (Sitara®)	Inhibition of biosynthesis of chitin and prostaglandin	Most of the sucking insects especially Hemipterans	(Dhaliwal and Arora 2003; Dhaliwal et al. 2006)
		Plumbagin	Derived from roots of Plumbago capensis (medicinal shrub), Inhibits ecdysis, have ovicidal effects, inhibits ecdysteroid biosynthesis, disrupt mating and reproduvtion of insects	Lepidopterous pests, like Pectinophora gossypiella, Helicoverpa Zea, H. virescens etc., red coton bugs,	

Categories	Major group	Active ingredient (Generic names)	Properties/mode of action/effects	Target insects	References
Sclerotization inhibitors or accelerators	Sclerotization inhibitors	Ditertiary butyl alcohol (MON-0585)	Reductions in the levels of covalently bound catechols, reduction in phenoloxidase activity, malformations in the exoskeleton	Mosquito and other dipterans	
	Sclerotization inhibitors	α-methyl DOPA	Inhibits DDC enzymes (3,4-dihydroxyphenyl alanine decarbosylase) and kills insect during molting	Dipterans	
	Sclerotization accelerators	Cryomazine	Produces necrotic lesions in cuticle, extra-hardens the cuticle by adding an extra cuticular layer between endo- and exo-cituctle, non-expansion of insec's cuticle	Dipterans like blowflies, housefly, etc.	
MH-agonists	Ecdysteroid agonist	chromafenozide (Virtu ®)	Contact and stomach action; interaction with the ecdysteroid receptor proteins; creates hyperecdysonism; synthesis and apolysis of cuticle but no sclerotization; feeding inhibition; larvae become dilapidated, slip their head capsule, and extrude their hind gut; death due to incomplete molting, starvation, and desiccation due to hemorrhage.		(Retnakaran et al. 1997; Dhadialla et al. 1998)
		Tebufenozide (Mimic ®, Confirm ®)	disrupt insect hormonal systems, and bind to the ecdysteroid receptors, thereby accelerating the molting process	Lepidoptera insects, especially, Spodoptera sp., Helicoverpa zea and Manduca sexta in cotton, cereal, maize, rice and vegetables.	(Smagghe and Degheele 1992; Palli et al. 1996)
		Halofenozide	Act as MACs (Molt Accelerating Compounds);	Lepidoptera, Coleoptera and some	(Potter 1998)
			Mimicking action of ecdysone, premature molting cessation of feeding and ultimately death of insects	Homoptera	
		Methoxyfenozide	Disruption of hormonal system; accelerating the molting process, hormonal imbalance, abnormal growth and development	Lepidoptera insects but more effective against budworm/bollworm and diamondback moth	(Wing 1988; Smagghe and Degheele 1998)

Categories	Major group	Active ingredient (Generic names)	Properties/mode of action/effects	Target insects	References
		Furan Tebufenozide	Inhibition of the activities various insecticides detoxifying enzymes like phenoloxidase, catalase, chitinase, superoxide dismutase, peroxidase acid phosphatase, carboxylesterase, glutathione S-transferase, MFO-O-demethylase; very high cytotoxicity.	Lepidoptera pests on crops and high security against the environment and non-target organisms	
MH-antagonists	Ecdysone antagonist	Diofenolan	Delay in larval–larval and larval–pupal ecdysis, ecdysial failure, mortality, severe reduction in pupation, deformed pupae, complete inhibition of adult emergence, and severely hamper the normal growth, development and metamorphosis	Lepidopteran pests and scale insects in fruit, field crops	(Streibert et al. 1994; Singh and Kumar 2011)
		Azadirectin (composed of 20 different compounds)	Inhibition of PTTH production; deformities after molts; reduced thriftiness; antifeeding and antioviposition effects; inhibit the development of egg, larvae and pupae; Block the molting of larvae and nymphs; disturb the mating and sexual communication; induce sterility in adults	Whiteflies, aphids, thrips, fungus gnats, caterpillar, beetles, mushroom flies, mealybugs, leafminers, moths and others on foods, greenhouse, crops, ornamental plants etc.	(Thomson 1992)
JHAs	Juvenile hormone agonists	Kinoprene	Juvenile hormone mimics, Juvenile hormone analogues	Culex pipiens Larvae; whiteflies, gnats, aphids, meal ybugs, and scales	(Hamaidia and Soltani 2014)
		Hydroprene	Juvenile hormone mimics; Juvenile hormone analogues; contact insecticides; abnormal or detrimental growth, development, and reproduction	stored-product insects, cockroaches	(Arthur et al. 2008)

Categories	Major group	Active ingredient (Generic names)	Properties/mode of action/effects	Target insects	References
		Methoprene	Juvenile hormone mimics; Juvenile hormone analogues; contact insecticides; abnormal or detrimental growth, development, and reproduction; prevent normal molting, egg-laying, egg-hatching, and development from the immature phase (i.e. caterpillar) to the adult phase	stored-product insects; beetles, flies, mosqu itoes, ants, moths, m ites, ticks, spiders	
		Fenoxycarb	non-neurotoxic carbamate insect growth regulator; ecdysis inhibition; suppresses reproduction; inhibits hatchability; mimics the action of the juvenile hormones on molting and reproduction; larvicide, ovicide	public health insects, ncluding cockroaches, fleas, stored product pests, ants, mosquito larvae, moths, scale insects, and insects attacking vines, olives, cotton and fruit	(Edwards et al. 1991; Grenier and Grenier 1993)
		Pyriproxyfen	Juvenile hormone mimics; contact insecticides; abnormal or detrimental growth, development, and reproduction	stored-product insects; field crop pests, mosquitoes, ants, cockroaches	(Richardson and Lagos 2007; Kabashima et al. 2007)
		Juvabione and Dehydrojuvabion	Stifling of insect reproduction and growth; inhibits embryogenesis and eclosion from the egg, induce insect sterility	Stored grains insects, whitefly, aphids and other sucking insects,	(Metwally and Landa 1972)
AJHAs	Juvenile hormone antagonists	Precocene-I, Prococene-II Precocene-III	cytotoxic action on the corpora allata ; Inhibits juvenile hormone biosynthesis and ovarian activation; alters sterility; disrupt the vitellogenesis in eggs inside the ovary; delays moulting; inhibits melanation, sclerotization, sexual maturity; causes a decrease in dry weight and protein content of the cuticle; causes decoloration	Majority of insects belonging to homopterans, hemipterans, orthopteran, dictyopterans, coleopterans; Lepidopterans; isopterans, hymenopterans, etc.	(Eid et al. 1988)

8.5. Conclusions

Biorational products denote biomolecules of natural origin that are active against pest populations, but relatively innocuous to nontarget organisms due to their low or no direct toxicity. Conventional insecticides are imposing sever health hazard effects and serving as a major source for ecological backlashes because they mostly target those systems of insect which have physiology exactly like that of higher animals and human being. Biorational products/approaches are based on the growth and development as well as communication system of insects which is quite different from that of higher animals and human being. Plant based secondary metabolites or phytoalexins involved in plant defense show insecticidal activities and can be employed in pest management program of various insect pest either by incorporating such molecules in insect diets (food traps) or cloning in transgenic plants. Semiochemicals are safe and eco-friendly substances without leaving any residues in the environment that's why they should be exploited for insect-pest management. Generally, biorational products are slow acting as compared to conventional nerve poisons. But the end users want that insects should die within no time and crop should be free of pests after insecticides application. This attitude and thinking of the end-user is a big hurdle in the acceptance of biorationals as pest management tool. This necessitates that distributors and users should be educated about the mode of action and safety of the biorational products. These products have great potential for replacing the persistent conventional insecticides, confirming effective cost-benefit-ratio, tackling ecological backlashes and ensuring food security with safe environment and enhanced exports. Unlike broad spectrum conventional insecticides, biorational products are highly target specific and commanding no or little mammalian toxicity or toxic effects on non-target organism. Such products have short residual activity that's why they should be employed when pest-insects are in their most susceptible life stages. The molecules used as biorational products are very active at very low concentration, safe for natural enemies of insect pests, do not accumulate in the environment and are degraded to simple nontoxic molecules. However, the large scale utilization of the biorational products undergoes some limitations. A huge amount of investment is involved in the development and marketing of biorational products. Their specificity to one species or closely related species limits their marketing potential. Similarly, most of the biorational molecules are photodegradable and face rapid reduction in their efficacy. Some biorational products like semiochemicals require area-wide application for getting effective and economical results.

The issues associated with biorational insecticides are not overwhelming; rather are addressable. Both the fundamental and applied aspects of such biomolecules need a very comprehensive research. There is need to investigate analogues of such molecules to enhance their stability in the system. A comprehensive research is required to explore the genomic and proteomics of such molecules for their insertion in plants through biotechnological approaches and developing genetically modified resistant plant species of economical crops. In the new era of biotechnology, most of the issues associated with these biorational products have been solved and these products are not only winning the reliability of the market and end user but also demonstrating their worth and potential in sustainable IPM program of economic crops against insect pests.

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Chapter 9

Biotechnological Approaches for Sustainable Insect-Pest Management

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Abstract

To meet the fiber, food and other requirements of the growing world population, agricultural biotechnology is now an essential tool. Agricultural insect pests are a big threat as they damage crop yields all over the world computing to an annual loss of several million dollars. Genetically Modified (GM) Crops have been rapidly adopted worldwide to manage agricultural pests safely and effectively. Recently, crops expressing proteins from the bacterium *Bacillus thuringiensis* (*Bt*) have been developed by plant breeders that are highly resistant to many of our most serious insect pests. Transgenes from *B. thuringiensis*, are increasingly used to protect the staplecrops and vegetables from insect damage. In this chapter, we will discuss and review the role and application of biotechnology, different methods and techniques such as RNA interference technology (RNAi) and Sterile Insect Techniques (SIT) that have been proven to provide sophisticated alternative tools for targeted control

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of insect pests of different crops (cotton, maize, rice, vegetables comprising mainly potatoes and also fruits etc) for sustainable agriculture. Moreover, the chapter also provides valuable information and scientific knowledge about the methods and techniques used in the development of transgenic crops having insecticidal proteins and the importance of their use within an IPM context.

Keywords: Biotechnology, RNAi, Sterile Insect Technique, Entomopathogens, GM crops

9.1. Introduction

Insect pests have become a menace and are posing a serious threat to worldwide agriculture. Despite all the remedies and techniques deployed by farmers to protect crop plants, this issue has still not been properly solved. After the Second World War, the production of warheads decreased due to a decline in their demand which unfortunately led to the shifting of the warhead industry to production of insecticides/pesticides. In order to improve their business, the multinational companies pushed for the application of pesticides promising farmers that after some years of pesticide application, the pests would be completely eliminated. Farmers were tempted to use high inputs of pesticides in the hope of getting higher crop yields. Pesticide application gradually became more common and eventually farmers started relying entirely on pesticides to kill insects/pathogens. Even scientists shifted their attention towards production of new and powerful insecticides instead of working on development of insect resistant crop plants (Smith and Kennedy 2002). However, with the passage of time it is now being realized that this practice has gradually increased the resistance in insects (Lee 1992) as well as causing serious health hazards and adverse environmental effects all over the globe. Moreover, the massive use of broad-spectrum insecticides/pesticides has badly disrupted the ecosystem of natural predators and parasitoids that helped in controlling different pests. After the realization of this situation, there was a dire need to find a permanent and environment friendly solution to this problem. This was only possible by integrated pest management or biotechnological approaches through which insect resistant varieties of important crop plants were tailored along with maintaining a healthy ecosystem (Gelernter 2005; Boschm and Gilligan 2008).

Due to the growing dependence on insecticides, which harm the environment and human health, entomologists developed an "integrated pest management" (IPM) strategy to control insect pests (Kogan 1998; Koul et al. 2004). IPM is generally defined as "a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost/benefit analyses that take into account the interests of; and impacts on producers, society, and the environment". It involves the non-genetic approach which combines the use of chemical control, resistant germplasm, crop rotations to interfere with insect life cycles and modification of plant handling and harvesting methods (Carrozi and Koziel 1997).

The IPM strategy is mainly based on the prevention and management of pests by planning tactics to use before the injurious stage of the pest. These include host plant resistance (HPR), cultural control, biological control and limited use of insecticides. However, this approach has not proven to be 100% successful.

The discovery of polymerase chain reaction (PCR) by Mullis and Faloona (1987) remarkably facilitated the DNA marker technology. Tremendous advances in forensic studies, crop breeding, human DNA fingerprinting, solutions for criminal and paternity disputes, early detection of diseases, gene cloning and engineering of organisms has been achieved through the tools and techniques of biotechnology (Kramer 2002). The field of agricultural biotechnology is progressing tremendously over the last 30 years due to the greater understanding of DNA as the blue print of genetic code. Biotechnology will serve as bridge to move our agriculture industry forward to help meet the food and fiber needs of the growing world population.

Genetic engineering is a term that is often interchangeably used with gene technology, genetic modification, or gene manipulation. Basically, it refers to the alteration of the genetic make-up of an individual using recombinant DNA tools. Through this technique specific recombinant enzymes are used to cut and insert pieces of foreign DNA into a plasmid vector which is in turn used to clone the gene of interest. This technique is similar to breeding as it also uses the principles of genetic manipulation; however in traditional plant breeding, the genes are transferred between the same species while in genetic engineering, genes may be transferred to individuals that would not interbreed in normal circumstances. Conventional breeding approaches are very laborious and time consuming. Moreover, there are chances of transfer of undesirable genes or while one desirable gene is gained, another maybe lost due to random assortment of genes in the offspring. Due to these reasons, traditional breeding approaches have not succeeded in improving agriculture to a high extent (Primrose and Twyman 2006).

Recent scientific breakthroughs in molecular biology made it possible to target pests and their insect vectors directly. Biotech crops (GM crops) offer a promising future for sustainable pest management through which pests may be controlled safely and effectively without the use of pesticides (George 2008). All genetic engineering approaches do not involve insertion of new genes. Genetic make-up of plants may also by manipulated by removing or switching off certain genes or their promoters. The increasing knowledge about insect genomes and advent of RNA interference technology may be combined to develop crops expressing double stranded RNA mediated silencing of genes in pests and insects without obstructing non-target organisms. Additionally, other approaches such as RNAi/insect transgenesis and sterile insect techniques have been proven to provide sophisticated alternative tools for targeted control of pests and their insect vectors (O' Brochta and Atkinson 2004; Robinson and Hendrichs 2005).

"Green biotechnology" may profit from the raising spectrum of insect-derived genes encoding anti-microbial peptides whose transgenic expression hve been established to confer crop resistance against economically important phytopathogens and insect pests. This chapter addresses the input of biotechnology in modern and sustainable approaches for plant protection and pest management. This chapter also explains the biotechnological approaches/methods and techniques for the development of GM crops for sustainable pest management.

9.2. Application of biotechnology in insect pest management

Biotechnology is basically the effective use of living systems and organisms to develop or make useful products for human beings, or "any technological application that uses biological systems, living organisms or derivatives thereof, to make or modify products or processes for specific use". Plant diseases caused by insect pests damage crop yield all over the world computing to an annual loss of $30-50 billion (Misra and Bhargawa 2007). However, genetic engineering and biotechnology have made it possible to produce crop plants with improved resistance against such bioagressors. Molecular biology approaches have helped scientists to support and enhance worldwide plant health. Although biotechnology involves a wide range of complex and diversified tools and techniques, its basic principles are quite simple. It is necessary that the proper knowledge of the physiological and biological mechanisms of action and regulation of gene expression as well as bio-safety measures must be ensured beforehand. Some major achievements and uses of biotechnology for increasing crop production by protecting them from insect pests are discussed below:

9.2.1. Peptides

Peptides or proteins with an anti-pest infection activity have an immensely high potential for sustainable plant protection. For example microbial peptides from the bacterium *Bacillus thuringiensis* (*Bt*) show activity against various insects (James 2008). These days' insecticidal *Bt* peptides are being used in combination with other traits like herbicide tolerance; thus enhancing the potential of antimicrobial peptides (AMPs) (Marcos et al. 2008) as Cecropin was recognized as the first AMP in the 1990s. It was extracted from insects and applied ectopically on crops such as potato and rice to increase their insect resistance. The spontaneous production of insecticidal peptides/proteins is one of the responses in plants against the attack by phytophagous insects. A lot of experiments have been conducted in the last 10 years to study the activity of a few lectins that are expressed in response to herbivory by phytophagous insects (Killiny et al. 2012). They can be used in developing various insect pest management programs as they have little effect on non-target organisms. Carbohydrate-binding proteins (CBP) or lectins are a group of entomotoxic proteins present in many plant species. They may be used to control pests (Killiny et al. 2012).

The venoms of certain insects are also being used to topically kill various insect pests, e.g., spider venoms are complex mixtures of toxic chemicals (Tedford et al. 2004). The venom of the Australian funnel web spider (*Hadronyche versuta* S.) containing the x-ACTX-Hv1a toxin (Hvt) effectively killed the American bollworm (*Helicoverpa armigera* H.) and Egyptian cotton worm (*Spodoptera littoralis* B.) caterpillars when applied topically. The Hvt toxin when genetically expressed in tobacco, it protected the plants from *H. armigera* and *S. littoralis* larvae (Khan et al. 2006).

Some polypeptides from insect parasitoids and viruses are being identified and used to control insect pests. Baculoviruses or Nucleopolyhedroviruses are pathogens having double-stranded DNA. They are usually extremely small and attack insects and other arthropods. Their genetic material is extremely sensitive. The baculovirus particle (*virion*) is protected by protein coat called a *polyhedron* which is typically fatal to the insect (Granados and Federici 1986). Nuclear polyhedrosis virus (NPV) *(S. litura)*, corn earworm polyhedrosis virus *(Helicoverpa zea B.)* American bollworm polyhedrosis virus *(H. armigera H.)*, Cabbage armyworm (*Mamestra brassicae* L.), Diamond back moth (*Plutella Xylotella*), and cabbage butterfly (*Pieris brassicae*) nuclear polyhedrosis viruses have been identified and used successfully to control lepidopterous insect pests (Ahmad et al. 2016b). Some of them are commercially available baculoviruses that are being used to control insect pests of cotton, vegetables, corn and tomatoes (Mahr et al. 2008; Ahmad et al. 2016b). The Polydnaviruses (PDVs), such as Ichnoviruses (IVs) (Hymenoptera: Ichneumonidae) and Bracoviruses (BVs) (Hymenoptera: Ichneumonidae) are a family of insect viruses that are being isolated and used to control lepidopterous insect pest.

9.2.2. RNA interference (RNAi) technology

RNA interference technique (RNAi) was discovered for the first time in the soil nematode (*Caenorhabditis elegans* M.). RNA interference is a promising technology which may enable selected measures against insect pests without impeding non-target organisms. It is a powerful technique in which gene expression in a wide range of organisms may be down regulated through double stranded RNA. In this technique, plant-delivered RNA is used to suppress the expression of a particular gene in the pest. Down regulation of gene expression in insect pests through delivery of dsRNA can cause death of the pest by interfering with developmental processes and its metabolism. For example, Citrus greening is a rapidly spreading disease causing huge losses to the citrus industry all over the world. The citrus greening disease is also called the Huanglongbing (HLB) disease. It is spread by the phloem dwelling bacterium *Candidadtus Liberibacter asiaticus* (CLas) through the Asian citrus psyllid (*Diaphorina citri* K.) insect vector. Scientists of the Citrus Research and Education Center, University of Florida have used RNAi technique to induce abnormal/deformed wing in the psyllids. The abnormal wing disc gene "awd" associated with wing development in insects interferes with the flight of psyllids and thereby reduces their survival rate which eventually leads to control of the citrus greening disease (El-Shesheny et al. 2013; Hajeri et al. 2014). The red flour beetle (*Tribolium confusum* D.) shows a very strong systemic response to RNA interference. In this regard experiments have also been conducted in which expression of dsRNAs against insect genes in transgenic plants were studied. Plants have shown resistance against insect herbivory and the termite *Reticulitremes flavipes* juveniles (Zhou et al. 2008). Plants release certain chemicals which attract insects. If we are successful in suppression of the production of such chemicals, the plant may be protected (Carrozi and Koziel 1997). The suppression of gene expression by dsRNAs in herbivorous insects such as lepidopteran lightbrown apple moth larvae, *Epiphyas postvittana* (W.) (Turner et al. 2006) larvae of American bollworm (*Helicoverpa armigera* H.) and larvae of diamondback moth *Plutella xylostella* (L.) was successful (Kumar et al. 2009). RNAi technology has indeed a very huge potential in attaining insect resistance in plants. This is a useful approach having an immense potential for effective pest management. However, suppression of gene expression in insects has yet to be explored and more research both at basic and applied levels is required.

9.2.3. Transgene-improved sterile insect technique

Insect transgenic technology is a promising tool for insect control. Improvement in the Sterile Insect Technique (SIT) through transgenic approach might provide a new insight in to insect pest management. The SIT is an effective and ecologically safe method for controlling pests. In this system a mass of sterilized organisms or pests is reared in artificial settings and then released into nature, which leads to infertile mating in turn resulting in a reduction in the pest population (Klassen and Curtis 2005). The SIT is an environmentally friendly approach which may be used as an alternative to insecticides. Insect pests such as the pink bollworm *Pectinophora gossypiella* (S.) have been successfully eradicated through this technique in California, USA (Henneberry 2007). Moreover, the tsetse fly (*Glossina austeni* N.) in Zanzibar, the new world screwworm *Cochliomyia hominivorax* (C.) in North and Central America and various species of the tephritid fruit fly have been controlled in many parts of the world (Klassen and Curtis 2005). The Mediterranean fly (*Ceratitis Capitata* W.) has also been controlled by male-only releases (Hendrichs et al. 1995).

9.2.4. Manipulation of insect resistant molecular markers

Frego bract is a mutated type of floral bract in cotton. It is an important insect resistant trait. Due to its narrow and twisted shape, it does not allow insect eggs to stay on its surface. The eggs laid by insects on such bracts become more prone to environmental vagaries as compared to the normal broad bracts. The eggs tend to fall off from this thin and narrow bract. Although this trait seems a promising insect resistant trait, very little research work has been conducted on the trait and no commercial variety has been tailored. The frego-bract character was reported as effective in suppressing boll weevil (*Anthonomus grandis* B.) population and comparison of the fibre properties of frego lines with commercial varieties showed that it would be a useful trait for the development of insect resistant cotton cultivars (Jenkins and Parrott 1971).According to a report, cotton varieties having a combination of frego bract and red plant color could be developed which would be equal in yield and fibre quality with other commercial varieties (Weaver and Reddy 1977). However, according to some reports, frego bract genotypes are less productive and their fibre is of low quality (Thaxton et al. 1985; Singh 2004). Malik et al. (2009) found that frego bract recombinant lines are equally productive, have high photosynthetic rates and have a good quality fibre compared to the normal bract line. The variation between normal bract and frego bract recombinant lines was also determined by PCR studies and it was concluded that this useful trait can be incorporated into commercial cotton varieties for insect resistance by cloning the underlying gene for frego bract (Malik et al. 2009). In addition to frego bract, some other morphological traits have been identified which confer resistance to insect pests in cotton. Incorporation of such traits in the cotton cultivars has been advocated for stable, economic and environment friendly insect resistance in cotton by many researchers (Maxwell and Jennings 1980, Rahman et al. 2013). These traits include trichomes, okra leaf, nectariless, gossypol glands etc. which make cotton plant unattractive to insects for feeding, oviposition, shelter etc. Moreover, plant surface waxes also help in keeping insects away in sorghum, brassica, apple and rice. Trichomeshairiness on leaves and stems is a major source of resistance to many insects especially thrips and weevil (Stephens and Lee 1961) jassid and mites (Narayanan et al. 1990). Trichomes interfere with insect locomotion, oviposition, attachment, shelter, feeding, ingestion and digestion. They have shown to decrease the infestation of aphids and leafhoppers in potatoes and alfalfa (Floyd et al. 2002).

Hairiness is a major source of resistance against sucking insects in cotton (Mursal 1994). Rahman et al. (2013) identified DNA markers for velvet hairiness in cotton. Such insect resistant trait markers may be identified in other species and may be exploited in developing insect resistant crop cultivars. Insect resistance is a complex quantitative trait. QTL (Quantitative Trait Loci) Mapping studies for tungro spherical virus and green leafhopper (*Amrasca bigutulla*) resistance have been conducted (Sebastian et al. 1996). Similarly loci for the Russian wheat aphid resistance have been mapped in barley (Nieto-Lopez and Blake 1994). Moreover, the loci for gall midge resistance in rice (Nair et al. 1995), trichome-mediated resistance in potato (Bonierbale et al. 1994) and European corn borer resistance in maize (Christensen et al. 1994) have also been identified. Identification of molecular markers/QTLs can positively assist in breeding for insect resistance. New varieties of crops may be introduced through marker assisted molecular breeding. Once the underlying genes for insect resistance are identified, they may be cloned and integrated into commercial cultivars through transformation approaches.

9.2.5. Genetically Engineered Entomopathogenic Organisms

In order to avoid pollution and contamination of the natural ecosystem, effective and safe biocontrol agents have been introduced through biotechnology and genetic engineering. These biocontrol agents including fungi, nematodes, bacteria and viruses have proven to be highly effective against common insect pests which destroy our crops. These biocontrol agents are more popularly referred to as bioinsecticides.They do not leave toxic residues and are also safe for non-target pests (Robert and Bonning 2000).

Genetic engineering of biocontrol agents includes selection of the beneficial or required strains, cloning of genes that influence the certain trait of interest and then introducing these genes into the natural population in such a way that they are successfully expressed and multiplied in the progeny. All this depends on how much we understand the biology of pathogenicity. Most progress in this field is made in case of the baculovirus insecticides. The genetic manipulation of entomopathogenic fungi and nematodes is still in the initial stages of development and testing. A review of recent progress made in case of entomopathogenic organisms is given below:

9.2.5.1. Entomopathogenic Fungi

Entomopathogenic fungi produce a wide range of insecticidal proteins; however, these have not been exploited in agricultural biotechnological approaches. Some fungi such as *Beauveria bassiana and Metarhizium anisopliae* have a broad host range so may be used for effective biocontrol of its insect pests. The entomopathogenic fungi enter the host cuticle with the help of certain cuticle degrading enzymes. These enzymes along with serving as a means to penetration of the cuticle, also act as insecticidal proteins (St. Leger et al. 1998). The complex interactions between entomopathogenic fungi and its host insects have now been studied and researchers have come up with a successfully engineered entomopathogenic fungus *M. anisopliae*, which is highly effective against lepidopteran larvae (St. Leger et al. 1998; Robert and Bonning 2000).

Despite the 700 species of entomopathogenic fungi known, only one has been genetically engineered up till now. The main reason for little or slow progress in the development of entomopathogenic fungi is the little or no knowledge about the molecular biology of its pathogenicity. Moreover, good cloning systems are available for only a few species of deuteromycetes (Goettel et al. 1989). More fungal genes involved in pathogenicity need to be identified. It is said that various genes are expressed at various stages of fungal-host relationship (St. Leger 1993). *M. anisopliae* takes around 5 to 10 days to kill a host insect so scientists have genetically manipulated its genome in such a way that additional copies of the *Pr1* gene have been introduced which facilitate its penetration into the cuticle (St. Leger et al. 1996). Larvae infected with recombinant strains of fungus died earlier than those infected with the wild type *M. anisopliae*. *Pr1* also activates the trypsins which start melanization of the larvae. This reduces contamination of the environment as the melanization of larvae restricts the fungus sporulation and in turn dissemination of spores from one place to another (St. Leger et al. 1998).

9.2.5.2. Entomopathogenic Bacteria

Relatively more amount of work has been conducted on entomopathogenic bacteria as they are easy to culture and genetically manipulate via their plasmids. The most emphasis has been put on *B. thuringiensis* (Bt). Bt toxins are known for their specificity and safe nature. *Bt* produces several insecticidal crystal proteins (ICPs). These ICPs accumulate in the cytoplasm in crystalline form and are highly toxic against lepidoptera, diptera and coleopteran larvae. Next to *Bt*, a lot of work has been conducted on genetical improvement of Enterobacteriaceae which are kept in the guts of nematodes and then released into the hemocoel of *B. sphaericus* for mosquito control. The mosquito larvicidal genes have been cloned from *B. sphaericus* and are being genetically pyramided for infection of dipteral insects (Robert and Bonning 2000). Genetically engineered endophytic microbes are highly valuable in the sense that they may be used to kill stem and leaf feeding lepidopteran insects. The gene encoding Cr1Ac has been manipulated into the endophtic bacterium *Clavibacter xyli* (Tomasino et al. 1995). This bacterium was introduced into corn seedlings through seed inoculation or wounding. It was found that the damage caused by the European corn borer *Ostrinia nubilalis* was reduced from 55% to 65%.

9.2.5.3. Entomopathogenic Viruses

A variety of existing peptides or toxins are ineffective against insect pests when ingested or topically applied. Certain insect viruses such as baculoviruses help these toxins reach the site of action in the hemocoel of the insect. The viruses expressing neurotoxins are the most effective biocontrol agents and may be used as bioinsecticides. Baculoviruses are the only viruses genetically altered to act as bio-insectcides (Black et al. 1997). Around 20 recombinant baculoviruses have been successfully engineered up till now. The development of recombinant insect virus requires a plasmid transfer vector consisting of a viral genomic restriction fragment containing the desired sequence/alteration. The alteration is incorporated into the viral genome by homologous recombination between the parent genome and transfer vector. In order to produce a recombinant virus, it is necessary for the insecticidal protein to have no effect on the replication of the virus in host insect until the insect dies. Moreover the protein must be highly effective in small doses and must have a speedy reaction (Possee et al. 1997). *Autographa californica multicapsid nucleopolyhedrovirus* (AcMNPV) is the most studied virus in this context. The gene coding for polyhedral envelope protein was deleted from the AcMNPV genome which resulted in a 6 times greater and faster infection of the virus against the insect ‘first star’ *Trichoplusia ni* compared to the wild type AcMNPV which had that gene intact. This is due to the fact that rapid release of the virus into the gut of the insect leads to faster death. The promoters driving certain insecticidal genes are also activated early on in the life cycle of a virus to increase its efficiency. American Cyanamid and DuPont Company tested the first ever genetically engineered baculoviruses as bioinsecticides (Black et al. 1997). Small scale field trials of these bio-insecticides are being conducted and soon baculovirus insecticides will be on the market.

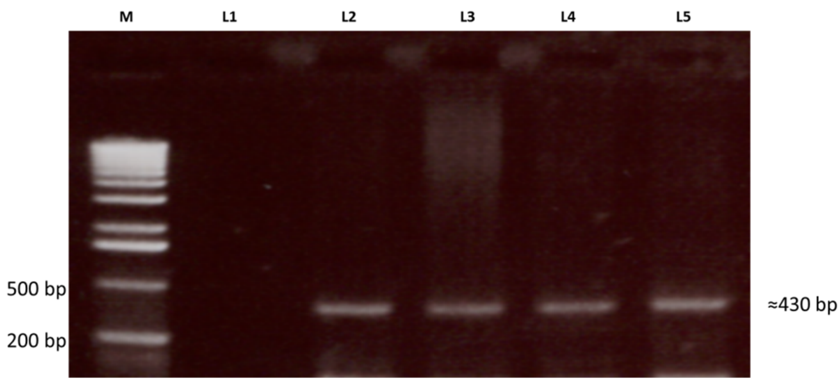

Fig.1A PCR for the detection of NPV from infected samples from different Geographical regions of Pakistan by using NPV specific primers: L1 Non infected *Spodoptera litura* Larva, L2- NPV infected *Spodoptera litura* larva (RY Khan strain), L3-NPV infected *Spodoptera litura* larva (Multan Strain), L4- NPV infected *Spodoptera litura l*arva (Faisalabad strain), L5- +NPV *Spodoptera litura* DNA, M- 1 kb DNA Marker. (Ahmad et al. 2016b)

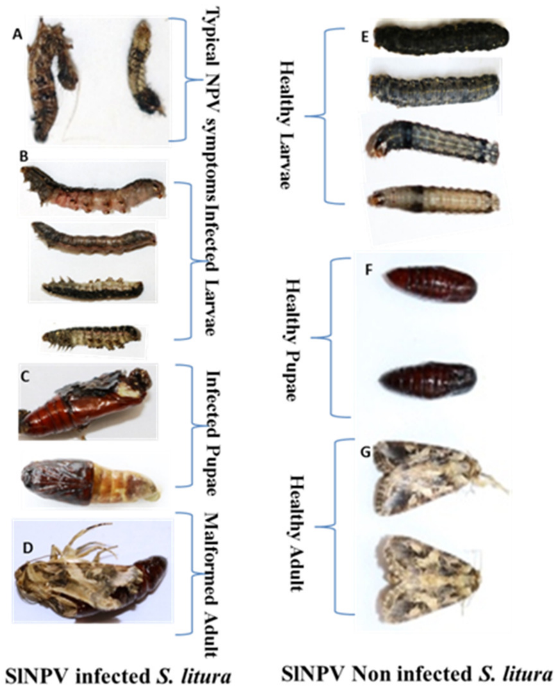

Fig.1B. Different stages of Healthy and NPV infected *Spodoptera litura* . ***A-*** typical NPV symptom as attached with walls of vials downward. **B-** Different NPV infected dead instars. **C-** NPV infected pupae. **D-** Malformed NPV infected Adults. **E.** Healthy larvae. **F-** Healthy pupae. **G-** Healthy Adults (Ahmad et al. 2016b)

Despite the fact that entomopathogenic fungi, bacteria and virus have been genetically altered and are being used to some extent as biocontrol agents, there are some disadvantages. Some problems and limitations we are facing in this strategy are limited host range, slow mode of action and restricted persistence in the field (Robert and Bonning 2000). But all this can be dealt with by further genetic manipulation and in depth understanding of the molecular basis of pathogenicity.

9.2.6. Development of transgenic crops and insects

The time required for developing a transgenic plant varies in different crop species. It also depends on the gene and available resources as well as regulatory approval. The main technique involves a series of steps:

The first step is the isolation of nucleic acids (DNA or RNA). This is done by following a proper extraction protocol. The extracted nucleic acid (DNA/RNA) is precipitated in the form of thread-like pellets. The second step is cloning of the gene of interest. This is done by generating DNA fragments (cut by a restriction enzyme) and then joining them to a vector which is then allowed to multiply in a host cell. Vector having the desired sequences is selected, isolated and clones are produced.

To determine whether the desired gene was cloned completely, the restriction enzymes are again used. Gene manipulation is further done by replacing an existing promoter sequence with a new one, adding a selectable marker and promoter gene and incorporating gene enhancer fragments and introns (Lemaux 2008).

While developing GM plants, promoters are used for differential expression of genes. Selectable marker genes are generally linked to the gene of interest to help in its detection inside the plant tissues. For this purpose antibiotic resistance and herbicide resistance marker genes are used so that the cells containing the inserted gene may be detected. Reporter genes are also cloned into the vector in close proximity to the gene of interest so that after transformation, the transformed cells may be easily identified. The reporter genes are also used to determine the correct expression of the inserted gene. Instead of inserting a whole new gene into an organism, gene expression can also be promoted by cloning genetic sequences in front of the promoter sequences or within a certain genetic sequence itself (Lemaux 2008).

Transformation is the most common method used to introduce a gene into the plant/animal cell. This is done through various techniques such as partial bombardment, gene gun method or through the use of the *Agrobacterium* bacteria. The transformed cells are grown *in vitro* and then cultured to form small plants expressing the inserted gene. The aim of transformation is to introduce the gene of interest into the nucleus of the cell without killing the cell and allowing it to continue its normal activities. Once a plant stably inherits and expresses the gene of interest in subsequent generations, it is called “transgenic”. PCR (Polymerase chain reaction) is one of the quickest and most effective methods used to determine the integrity of the transgene in the plant cell (Lemaux 2009). The detection of transgenic cells is done by analysis of PCR products in agarose gel to see whether the DNA fragment equivalent in size to the inserted gene has been amplified or not.

Another method used to expose the transgenic status of the plant is called Southern Blot analysis in which autoradiography is used. Northern blot analysis determines whether the transcript or the messenger RNA (mRNA) of the introduced DNA is present and is correctly transcribed in the transgenic plant. This is also done through autoradiography. Western blot analysis is an analytical technique used to detect whether the transgenic plants are producing the specific protein product of the inserted gene. Protein samples are extracted from the transgenic plant cells, denatured and then transferred to a nitrocellulose membrane. The protein is then detected by using probes or antibodies specific to the target protein (Towbin et al. 1979).

9.2.7. GM crops

Pest management technologies and practices in agriculture are cutting down the use of insecticides, the most prominent being the use of biotechnology. With the discovery of restriction enzymes in the 1980s, the field of molecular biology has progressed tremendously. After the first transformation experiments conducted on tobacco in 1983, *Bt* and some other insecticidal genes/proteins have been transferred to some crop plants to confer protection against insect pests. Scientific evidence strongly suggests that the GM crops grown so far are very safe and non-hazardous to the environment. Most of the GM (genetically modified) crops are known as *Bt* crops (due to the insertion of *Bt* gene). The benefits of *Bt* crops over the conventional varieties have been recognized all over the world and these insect resistant crops have been successfully grown on millions of hectares (James 2008). Crops such as maize, cotton, potato and rice, egg plant, and some cruciferous vegetables have been transformed successfully with *cry* genes coding for proteins that are highly active against the most important pests (Ferre et al., 2008). *Bt* crops, especially cotton contains *cry1Ac* or a fusion of *cry1Ac* and *cry1Ab* genes that are highly active against the lepidopteran (chewing pests) that feed on the cotton bolls. The *Bt* genes express a protein product which makes the cotton bolls toxic; so that whenever a pest tries to chew on the boll, the poison enters its gut eventually killing the pest (Ferre et al. 2008).

Recently we have developed a new plant system in oil seed rape (*Brassica napus* L.) lacking toxic mines and improving the quality of oil and fodder. We are investigating the defense response against sucking and chewing insect pests to control them in a proper way (Ahmad et al., 2016a).

The Colorado potato beetle poses a serious threat to the potato crop. Genetically modified *Bt* potatoes containing the *cry3Aa* gene against the Colorado potato beetle *Leptinotarsa decemlineata* (Coleoptera: Chrysomelidae,) have been planted commercially in North America and Europe. The development of a *Bt* rice product containing both *cry1Ac* and *cry1Ab* to offer complete protection against the rice stem borers is under pavement. *Bt* vegetable crops such as eggplant and cruciferous vegetables are also under development. In *Bt* eggplant, the eggplant fruit and shoot borer *Leucinodes orbonalis* (Lepidoptera: Pyralidae) is targeted while the diamondback moth *Plutella xylostella* (Lepidoptera: Plutellidae) is trying to be controlled by *Bt* crucifer vegetables (Shelton et al. 2008).

Some crops such as corn and soybeans have been genetically modified to resist herbicides. These crops now help farmers to eliminate the milkweed growing in between the rows of these plants without affecting the corn or soybean plants. These crops have been modified to be tolerant against the chemical glyphosate which is found in most herbicides (Losey et al. 1999).

9.2.7.1. GM cotton

Cotton is one of the world's leading fiber crops being grown in more than 75 countries with a total production of more than 26.6 billion kilograms. It fulfils 40% of the total worldwide fiber demand. China is the highest cotton producer in the world followed by India, USA, Pakistan and Brazil (Cotton production Worldwide Statistics 2014). Four species of cotton *Gossypium herbaceum, G. arboretum, G. barbadense* and *G. hirsutum*, are mainly grown in Asia, Egypt, parts of western and South America as well as the West Indies (Rahman et al., 2014). The most grown species is *G. hirsutum*. Cotton seed is used in animal feed and also produces oil. A large diversity of arthropods (more than 1300 herbivorous insects) inhabits cotton all over the world (Naranjo 2011). A number of insect vectors are being reported with corresponding plant pathogens producing havoc in respective arenas (Ahmad et al. 2016b).

Transgenic *Bt* cotton (producing the proteins *Bt*; Cry1 and Cry2) was firstly grown on a commercial scale in Australia, Mexico and the USA in 1996 but has now spread to millions of hectares all over the globe. It has effectively reduced the use of insecticides by 94.5 million kilograms and improved cotton yield by US$7.5 billion. *Bt* cotton controls boll worms which are a serious and highly damaging pest for cotton worldwide. The USA, Australia and Mexico were the first countries to allow commercial cultivation of *Bt* cotton, followed by China and South Africa in 1997, Argentina in 1998, Colombia and India in 2002, and Brazil in 2005 (James 2008). In 2009 *Bt* cotton was planted on 15 million hectares in more than 11 countries reducing 140 million kg use of insecticides (Steven 2011). The hybrid cultivation approval for planting in India was increased from 4 in 2002 to 131 in 2007. Now India is the highest *Bt* cotton producer in the world followed by China, and then the USA. Pakistan being one of the top 5 cotton producing countries of the world has introduced several *Bt* cotton varieties indigenously. In fact *Bt* is the only transgenic crop being commercially cultivated in Pakistan. The *Bt* cotton varieties approved for cultivation this year include Tarzan-1, VH-259, MNH-886, BH-178, NS-141, CIM-599, FH-114, CIM-602, IR-NIBGE-3, FH-118, CIM-598, FH-142, Sitara 009, IR-NIBGE-824, A-One IUB-222, Sayaban-201, Sitara-11M, A-555, KZ-181, Tarzan-2 and CA-12 (Rahman et al. 2014).

The Cry1 or Cry2 carrying cottons are resistant to nearly all sorts of bollworms as well as a variety of other pests such as leaf worms, leaf perforators and semiloopers. However these single genes expressing cottons are not so effective against pests such as *Spodoptera* spp., *Trichoplusia ni*, *Pseudoplusia includes* and cutworms (James 2008). In 2015, *Helicoverpa armigera* H. and *Pectinophora gossypiella* (S) infestation and resistance has been reported on Bt cotton containing Cry 1Ac in Pakistan (Ahmad et al. 2016c). Now double gene expressing cottons (Bollgard II, WideStrike) have been produced and are being grown in Australia. These dual gene constructs have a broad spectrum of resistance against the Lepidoptera so they can control many pests that were previously left unharmed by the single gene constructs (Adamczyk and Gore 2004).

It has been 18 years now ever since *Bt* cotton was first cultivated. Despite its advantages, some negative impacts have been seen. Among the disadvantages of *Bt* cotton, one of the most disastrous effects is that the low or no use of insect repellent sprays has increased the population growths of non-target pests in many *Bt* cotton growing countries. Some pests such as green mirid (*Creontiades dilutus*), green vegetable bug (*Nezara viridula*), leaf hoppers (*Austroasca viridigrisea* and *Amrasca terraereginae*), and thrips (*Thrips tabaci*, *Frankliniella schultzei* and *F. occidentalis*) (Lei et al. 2003, Wilson et al. 2006) have become more prominent in Australia. Wu et al. (2002) reported that a complex of mirid plant bugs such as *Adelphocoris suturalis*, *A. lineolatus*, *Lygus lucorum*, and *L. pratensis* have become problematic in China. In Henan Province (USA), it was observed that populations of some sucking pests such as leafhoppers (*Empoasca biguttula*), cotton aphids (*Aphis gossypii*) and spider mites (*Tetranychus cinnabarinus*) increased in *Bt* cotton fields (Williams 2006). According to a report by Sharma et al. (2005) an outburst of pests such as tobacco caterpillar (*Spodoptera litura*), mealy bugs (*Pseudococcus corymbatus*, *Pulvinaria maxima*, and *Saissetia nigra*), thrips (*T. tabaci*) and okra leafhoppers (*Amrasca biguttula biguttula*) occurred in different regions of India and Pakistan.

9.2.7.2. GM rice

Rice (*Oryza sativa L.*) being one of the most widely eaten cereals is grown on an area of 152 million hectares of the world (FAO 2007). About 90% of the total rice produced in the world comes from Asia (Maclean et al. 2002). Rice is grown on approximately 5,559,750 acres of Pakistan with a total production of 4,500,000.00 tones (FAO 2013). Punjab province is the major contributor as 59 % of the rice growing area of the country is located there. Quite a few varieties of rice are grown in Pakistan, however the main ones are Basmati Rice (long grain rice, comprising of more than 50% of the total cultivation) and IRR6/9 (short grain rice, comprising of 40 % of the total cultivation) (FAO 2007).

A wide variety of insect pests such as Hemiptera, Diptera, Lepidoptera, and Coleoptera damage this crop all over the world (Dale 1994). Lepidopteran stem borers are chronic pests in all rice ecosystems. They account for a yield loss of 2.3% in Asia (Savary et al. 2000) with 3.1% loss in China (Sheng et al. 2003). However, the most important tropical and temperate species are the yellow stem borer, *Scirpophaga incertulas* (Pyralidae) and the striped stem borer, *Chilo suppressalis* (Crambidae) respectively. Stem borer damages the rice tillers during vegetative stage called dead hearts whereas at the reproductive stage, it causes the production of panicles containing unfilled grains called whiteheads. Some foliage feeders from the Lepidopera group also infest rice species. Among these leaf folders, *Cnaphalocrocis medinalis* and *Marasmia* spp. (Pyralidae) are the most common. Leaf folders being very visible to farmers stimulate them to use insecticides (Matteson 2000). However, they can be controlled without the application of insecticides as leaf folders cause the least amount of damage to rice because they only affect at the vegetative growth stage which can compensate for damage to foliage.

Scientists have identified several genes in rice germplasm having resistance to plant hoppers, leafhoppers and the Asian rice gall midge (*Orseolia oryzae*). They have been crossed through breeding to tailor modern rice varieties. Although thousands of different rice accessions have been studied and evaluated, genes resistant to lepidopteran rice pests have not been identified up till now (Heinrichs 1994). After the huge success of transgenic *Bt* technology in cotton, extensive research and experiments to form *Bt* rice have been conducted over the years. The *Bt* gene transformation in rice was reported for the first time by Fujimoto et al. (1993). Rice lines expressing *cry1Aa*, *cry1Ab*, *cry1Ac*, a *cry1Ab/cry1Ac* fusion, *cry1B*, *cry1C*, and *cry2A*, and a fusion of *cry1Ac* with *cry2A* genes, have been shown to be resistant to stem borers, leaf folders and other foliage-feeding Lepidoptera. In addition to cry toxins through *Bt* gene, some protease inhibitors have also been expressed in rice to enhance resistance against the chewing pests. Plant lectin genes have also been used to control plant hopper and leafhopper pests of rice through genetic engineering. Lectin gene from garlic (*Allium sativa* leaf agglutinin gene, *ASAL*) and snowdrop lectin gene, *Galanthus nivalus* agglutinin (*gna*), has been used to induce resistance in rice against plant hoppers and leafhoppers in laboratory and field tests (Saha et al. 2006). Field trials were also conducted in Pakistan, Spain, Iran and India (Mahmood-ur-Rahman et al. 2007). *Bt* Rice will bring prosperity for Pakistani farmers as well as industries and business activities as Pakistan exports about 2 million tons or about 10 percent of world trade annually. However, *Bt* rice is currently not being grown commercially in any country of the world. China has banned the commercial cultivation of *Bt* rice due to environmental and health concerns. Iran grew 4,000 ha of *Bt* rice for seed multiplication in 2005 (James 2008) but commercial production in Iran is not currently allowed.

9.2.7.3. GM Maize

Maize, *Zea mays* L. (corn), grown on 365 million hectares of the world producing about 750 million metric tons of grain per annum. It is the second most cultivated crop after rice. The largest producer of maize is the United States, followed by China, Brazil, Mexico, Argentina and lastly India being the least contributor (FAOSTAT 2007). Asia accounts for 30 % of the global maize growing area. In Pakistan maize is grown on an area of 2.4 million acres with an annual production of 3.25 million metric tons. Punjab and NWFP (North West Frontier Province/Khyber Pakhtunkhwa) are the largest producers contributing to about 30 and 60 % of the total production respectively. About 0.25 million acres of maize are grown in AJK (Azad Jamu Kashmir) (Business Recorder 2014).

Genetically-modified (GM) maize was first planted commercially in the United States in 1996 and in Canada in 1997 but now more than 24% of the worlds area is under *Bt* maize cultivation(James 2007). A single Cry protein was introduced into the first GM maize plants produced. This Cry toxin is resistant to European corn borer *Ostrinia nubilalis* (Lepidoptera: Crambidae) and other lepidopteran maize pests. *Bt* maize containing endotoxin proteins such as *cry1Ab*, *cry1Ac* or *cry9C* shows resistance against the European corn borer and the Mediterranean corn borer *Sesamia nonagriodes* (Lepidoptera: Noctuidae). *Bt* maize containing the transgenes *cry3Bb*, *cry34Ab* and *cry35Ab* are effective against the rootworms of the genus *Diabrotica* (Coleoptera: Chrysomelidae) (Richard et al. 2008). Recently, herbicide resistant maize containing genes/proteins introduced by Monsanto is being cultivated In Pakistan.

9.2.7.4. GM fruits and vegetables

Fruits and vegetables are vital for good health. However, they are subjected to severe pest infection. About 30 % of the insecticides/pesticides applied all over the world are used to control insect pests of vegetables. The problem of fruit and vegetable pest infestation is more acute in the developing countries which are inhabited by 83% of the world's population (Shelton et al. 2008). Most vegetables are consumed in India and China. Transgenic or genetically modified vegetables and fruits are providing new dimensions for pest control in these countries. Production of transgenic vegetables resistant to insects and insect-transmitted pathogens or viruses has been successful to some extent. It may be possible to confer resistance against multiple viruses if genes from different viruses are collected and pyramided within a single T-DNA region of a binary plasmid. Generally the coat protein (CP) is genetically engineered to confer virus resistance (Fuchs and Gonsalves 2007). Some virus resistant vegetable and fruit species have been engineered that express the CP genes. For example, papaya ring spot virus (PRSV) has been controlled by genetically modified papaya expressing the CP gene (*Carica papaya* L.). It was commercially released in Hawaii in 1998 (Gonsalves 1998). After its success in Hawaii, China also recommended the cultivation of this genetically modified papaya (Hautea et al. 1999).

Citrus is a popular fruit among young and old alike. A total of 108 million tones of citrus are produced in about 52 countries of the world. Brazil is the largest producer of citrus whereas Pakistan ranks at 13th position in the world (FAOSTAT 2007). However its production is badly affected by certain insect pests such as whitefly, citrus psylla, leaf miner and citrus caterpillar. Huanglongbing (HLB) disease is seriously threatening and causing considerable economic fatalities to the citrus industry. This disease is globally widespread. The bacterial pathogen responsible for this disease is transmitted by the Asian citrus psllyid (ACP) *Diaphorina citri* Kuwayama (Homoptera: Psyllidae). HLB can only be managed if its vector, ACP is controlled. The Psyllid nymphs and adults feed on the phloem sap of infected trees acquiring the *C*Las bacteria and transmit to healthy trees. Many attempts have been made to control the vectors through various biological/biochemical techniques. The parasite *Tamarixia radiata* was found to be effective in stopping the spread of these diseases as it is a natural enemy/predator of psylids (Baniqued 1998). Genetically modified citrus expressing the *Bt* endotoxin and a group of lectins (WGA, CoA, LL and PL) has been produced by a group of scientists working in the Department of Entomology and Nematology, University of Florida, USA observing increased ACP mortality in those GM citrus plants (Killiny et al. 2012). However these GM citrus lines have not been commercially released and more work is currently going on.

Potato (*Solanum tuberosum* L.) is a staple food in many parts of the globe. It is one of the most important food crops. It is ranked on fourth position after maize, rice and wheat. Potatoes are rich in antioxidants and have a high nutritious value. Unfortunately potatoes are attacked by a variety of insect pests, including insects that attack foliage and tubers e.g potato leafhopper (*L. decemlineata)*, potato tuber moth, *Phthorimaea operculella* and black cutworm, *Agrotis ipsilon* L.. The insertion of desired genes by genetic manipulation for developing new potato cultivars seems promising. Potatoes are not produced by seeds; they are propagated through tuber cuttings. They serve as a great challenge to plant breeders because *S. tuberosum* is tetraploid, making it difficult to manipulate the genes of choice between cultivars and have them expressed in progeny. So the insertion of genes of interest by genetic engineering and tailoring new potato cultivars seems promising. Potatoes were one of the first successful GM crop plants (An et al. 1986). However, the commercialization of genetically modified (GM) potato cultivars has not been so successful because Japanese and European markets are unwilling to accept them (Shelton et al. 2008). GM potato cultivars expressing the Cry3A *Bt* toxin are very effective against coleopteran pests such as *L. decemlineata* and were commercially available in the USA from 1996–2000. *Bt cry1Ia1* is effective against lepidopteran pests such as *P. operculella* (Douches et al. 2004). The *cry1Ac* and *cry1Ac9* gene has been shown to be effective against the tuber moth control (Davidson et al. 2005).

Potato cultivars carrying the *cry 3A* toxin for resistance against the Colorado potato beetle *Leptinotarsa* L. *decemlineata* were the first GM food crop approved for human use. They were commercially produced in the USA in 1995. Due to consumer concern, the *Bt* potato was banned from the market in 2000. GM potato cultivars resistant to aphids have not been produced yet. However, genetically modified varieties resistant to potato virus Y and potato leaf roll virus along with resistance to Colorado potato beetle were produced commercially for a short time and then they were also banned in 2000 along with the *Bt* potatoes. After this ban, potato virus Y is continuously spreading and no effective management has been devised (Davis et al. 2007).

Transgenic tomato and pepper resistant to CMV (Cucumber Mosaic Virus) through expression of the viral CP have been released in China. Further research on CMV resistant tomato is recently being conducted in Indonesia and the Philippines. It is predicted that more virus resistant vegetables and fruits will be released in future (Fuchs and Gonsalves 2007). We have depicted and displayed a novel research, first time in Pakistan, to control the important tomato virus vector silver leaf whitefly (*Bemisia tabaci* G.) via employment of *PR1a* and *PIN2* gene expressions via plant hormonal mediated defense systems (Ahmad et al. 2016a)

Bt tomato line 5345, resistant to lepidopteran insects was genetically engineered. The genetically modified tomato contains two novel proteins; Cry1Ac and neomycin phosphotransferase (NPTII). The Cry1Ac protein is effective against the lepidopteran insects, including the Colorado potato beetle. In mentiond vegetable crops,e.g., tomato, newly emerging pathogens such as phytoplasama can be detected and hence successively managed by advance molecular and genomic appraisals (Ahmad et al. 2016b).

Excitation and elicitation of plant defense and signalization seems to be vital and modern insect management suitability especially against American bollworm (*Helicoverpa armigera* H.), occuring on tomato, based on modern insect integrated genomics relied mechanics. Conclusive remarks, of our molecular study, revealed activation of signalizing genes of *PIN2* by phytohormones methyl jasmonate and suppression or impairment of benzothiadiazole responsive genes *PR1a,* favoring the better *H. armigera* percent reduction and decrement with simultaneous provisions of plant growth promoting rhizobacteria (PGPRs) mainly *Pseudomonas spp.* of bacteria.

Sweet corn is the only GM vegetable grown on commercial scale in USA these days. It expresses the *cry1Ab* endotoxin which is highly effective against Lepidoptera, European corn borer, *O. nubilalis* (Speese et al. 2005). The main advantage of this *Bt* sweet corn is its non-harmful behavior towards the insect predators of *O. nubilalis* (Hoheisel and Fleischer 2007) as well as a complex of epigeal coleopterans (Leslie et al. 2007).

Eggplant (*S. melongena* L.) is an annual plant and a very popular food crop grown in the tropical and sub-tropical regions of the world. However, it is affected by several destructive diseases such as *Phomopsis* blight, *Verticillium* wilt, and several viral diseases (Chen et al. 2001). Insects such as thrips, cotton leafhopper, jassids and aphids seriously damage this vegetable, the most damaging is the eggplant fruit and shoot borer (FSB), *Leucinodes orbonalis* Guenée (Lepidoptera: Crambidae). Farmers tend to use insecticides to get rid of these pests. However chemical control is not a sustainable solution. Maharashtra Hybrid Seeds Company Limited (Mahyco) transformed *cry1Ac* gene in the eggplant. The first transgenic eggplant resistant to FSB (FSBR egg plant) was developed in 2000.

Brassica vegetables including cabbage, cauliflower, broccoli, turnip, Chinese cabbage and mustards are grown in most parts of the world. They are mostly attacked by the Lepidopteran larvae especially the diamondback moth, *P. xylostella* (L.) (Lepidoptera: Plutellidae). It is responsible for up to 90% worldwide losses to cabbage and cauliflower accounting to yield losses up to 1 billion US dollars every year (Talekar and Shelton 1993). Cry1 *Bt* genes have been successfully expressed in several *Brassica* species, making them resistant to *P. xylostella* and other Lepidoptera (Paul et al. 2005).

9.2.7.5. GM Insects

A genetically modified insect is an insect that has been genetically modified for various reasons such as agricultural production, oil production and pest control. Insect transgenic technology will provide new dimensions for effective control of insect pests. Transgenic fruit flies (*Drosophila melanogaster*) also known as the vinegar flies are being used as a model plant in biological research to study genetics, physiology, microbial pathogenesis and life history evolution. Fruit fly is preferred over other animals due to its short life cycle, simple genome (only 4 pairs of chromosomes) and low maintenance requirements. Genetically modified mosquitoes were produced and released in the 1970s. The particular specie of mosquitoes held responsible for the transmission of the dangerous dengue virus were also sterilized by irradiation through the sterile insect technique (SIT). The British company Oxitec used a technique called RIDL that produces fertile adults but induces a high death rate of the descendants. The adults generated with this technique released in the environment are not sterile but their descendants have a survival rate of only about 5% (or much higher in presence of tetracycline) (D'Andrea 2013).

Although the SIT is already successfully applied for some species, however its various steps such as large scale rearing; sex separation for male-only releases and sterilization methods may be improved through the use of biotechnology to increase the efficiency of this program. Genetic control based on the SIT uses the approach of releasing a mass of artificially reared sterile insects so that they may cause infertile matings eventually reducing the level of pest population (Klassen and Curtis 2005). The SIT is considered an environmentally safe alternative to insecticides for insect species that can be artificially reared on a large scale. The SIT has been successfully employed in to suppress or get rid of pests such as the pink bollworm (*Pectinophora gossypiella* in California, USA (Henneberry 2007).

As stated earlier, the use of RNAi technology for controlling disease causing pests has shown a great potential. RNAi technology has been used in insects such as flour beetle (*Tribolium castaneum*) (Tomoyasu et al. 2008), light brown apple moth (Turner et al. 2006) and grasshopper (Dong and Friedrich 2005) as well as in adult mosquitoes through topical application method. Expression of dsRNA in transgenic plants also provides a continuous source of dsRNA for the feeding insects. When the insects feed on that certain plant, RNAi responses reach the midgut of insects, eventually leading to plant resistance against that particular pest. The dsRNAs can also be applied in the form of molecular pesticides after producing large amounts of dsRNA through the established bacterial expression system. The successful development and use of insect transgenic systems will help us understand the diverse aspects of biology answering many questions so far not addressable, eventually leading to sustainable agriculture.

9.3. Conclusion and future prospective

The challenge for any pest control measure or technique is to minimize negative effects on non-target insects as far as possible while allowing farmers to produce profitable crops. Massive use of pesticides/insecticides has led to destruction of our natural ecosystem and is posing serious problems for human health. Tailoring plants with built-in resistance to various insect pests serves as a remarkable strategy to control even the worst insect pests without having any hazardous effects to the environment. This is accomplished by engineering plants resistant to insects through genetic modification. Production of genetically modified crops is a safe and environmentally friendly approach for sustainable pest management. A considerable amount of work has been done on various crops and insects using the diversified tools of biotechnology. Scientists have been successful in development of *Bt* crops using the *Bt* endotoxin gene derived from *B. thuringiensis*. With the advent of these crops, a considerable decline in chemical control has been observed. For example, the pest pressure and damage potential in cotton crop is very high. It is seriously damaged by the Lepidopteran insects. Large amounts of broad-spectrum insecticides are used routinely on most conventionally grown cotton, resulting in damage to non-target insects and widespread insect pesticide resistance problems. In contrast, the *Bt* insect-resistant cotton seems to provide environmental benefits in many areas where it is now grown. The insecticide reduction is apparently clear in *Bt* cotton. Since there is an increasingly urgent need to balance food production and biodiversity conservation in our overpopulated world. GM crops, if developed carefully, tested rigorously and applied wisely, have the potential to provide at least some of the solutions to sustainable and environmentally benign world agriculture. This does not mean complacency and the uncritical acceptance of all crops developed using this technology, but it does require a thoughtful case-by-case rational approach.

China, India and Pakistan account for nearly 40% of the world's population. Insect pest problems are prevailing seriously in these countries so they have readily accepted the GM technology. All three of the countries have already adopted *Bt* cotton and it is likely that *Bt* rice will be commercialized in China in the near future. The adoption of GM crops in these countries leads to the probability of also accepting GM vegetables and fruits. Although GM vegetables seem promising for the management of insect pests and the diseases transmitted by them, however, they have not been so eagerly cultivated as other crops such as cotton and maize. Rice is a staple food in Asia. After the huge success of *Bt* cotton and *Bt* maize, *Bt* rice is gaining importance. It has the potential to eliminate pests from the rice fields in an eco-friendly way. However, *Bt* rice has still not been commercialized. Farmers are still reluctant to grow *Bt* rice may be due to the reason that it is not popular in foreign markets. More studies on the bio-safety and experimentation on wider scale under varying environments are required.

While the field of insect biotechnology is still at an infant stage, it has a tremendous potential to revolutionize agriculture and lead to a sustainable management of all the plant pathogenic problems faced by mankind. The use of genetic engineering to combat the problem of insect pests by increasing host plant resistance requires a comprehensive understanding of the crop plants as well as the complex physiology and biology of insects. There are quite a few mysteries about insects that are yet to unfold. Scientists are working on new insecticidal proteins such as cholesterol oxidase which is effective against boll weevil. Similarly vegetative insecticidal proteins for corn rootworm and black cutworm are on the verge of development. The SIT is an environmentally friendly approach which may be used as an alternative to insecticides. RNAi technology also has a huge potential in controlling insect pests through the use of biotechnological approaches. Moreover, identification of insect resistant molecular markers, insertion of novel insecticidal genes/proteins and multigene pathways as well as manipulation/replacement of existing genes through gene therapy may lead to development of highly insect resistant cultivars resulting in a sustainable solution of insect pests.

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Chapter 10

Integrated Pest Management, Past, Present and Future in a Changing World

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Abstract

Integrated pest management (IPM) is a sustainable approach to control agricultural crops pests. To evaluate the functionality and efficiency of IPM, the mechanism of plant response to herbivory is the first and foremost principle to understand. The chapter focuses on the past, present and future perspectives of IPM globally. Various sustainable management of insect pests case studies, challenges and success stories have been discussed and elaborated to reach the consequences and outcomes of IPM. The comprehensive litreature studies have proved that integrated pest management is a best practical approach to get sustainability in controlling the insect pests of various crops of economic importance.

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10.1. Integrated pest management- an overview

Integrated pest management (IPM) ranks among the most far-reaching and most comprehensive of crop production tactics being adopted by producers today (Higley and Pedigo 1996). IPM tactics are aimed at producing the highest possible crop yield with a minimum of expense to the producer and the minimum amount of harm to the environment. A major goal of IPM has been to conserve natural enemies and their effects when attempting to suppress pests. Specifically, IPM seeks to maintain crop and control sustainability and environmental quality while improving profits through the proper diagnosis of pests, empirically derived economic thresholds, and specific pesticide applications (Higley and Pedigo 1996). By implementing IPM practices, producers will slow pesticide resistance and reduce environmental contamination, including the reduction of pollution to water systems. Crop producers will be gain value from money spent on pesticides and those concerned with the environment gain comfort from knowing the minimum amount of pesticide is being used and only when substantial losses are predicted.

The idea of IPM was first formally advocated by Stern et al. (1959), but in 1934 a paper by Pierce (1934) posed questions that seemed almost prophetic to the agricultural community in their simplicity. The questions were "Does all damage computed by every single insect is assessable? If not, then when does it become assessable? What is the guarantee of control effectiveness even if the damage is below this point?" Essentially, Pierce was asking if there is a difference between injury and damage. And if there was a difference, where does the injury stop and where does damage begin? He set the stage for the development of Economic Injury (EIs) and Economic Thresholds Levels (ETLs) by asking when control measures are justified.

Pierce (1934) posed the core questions of the issue, but Stern et al. (1959) expanded on Pierce's work by discussing insecticide resistance, replacement, resurgence, residues, and non-target effects of insecticides in their 1959 paper. In order to implement IPM practices Stern et al. (1959) found it necessary to develop the concept of economic injury levels (EILs). They defined an EIL as "the lowest population density that will cause economic damage." This definition is still used in the application of EILs and today refers to the point at which injury inflicted by a pest becomes economic damage.

To minimize confusion, the term "damage" must be defined because damage and injury differ based on their effects on yield of marketable materials. "Injury" is the effect of pest activities on host physiology that is usually detrimental, while damage is an assessable loss of materials or decrease in their characteristics. Thus, damage is often defined as loss to amount of yield, yield quality, or aesthetics (Pedigo et al. 1986).

EILs can be powerful tools for crop producers when making management decisions, but the definition provided by Stern et al. (1959) was not sufficient for producers to adopt this method. Pedigo et al. (1986) refined the definition of EILs to be "the point at which the cost of control (pesticide and application) equals the cost of no control (yield loss)." Pedigo et al. constructed an equation explicitly defining an EIL as:

$$EIL = C/VDIK$$

Where C = management costs per production unit, V = value per unit production, D = damage (yield loss) per unit injury, I = injury per pest, and K = proportion of injury prevented by management.

This definition is a step forward in the evolution of applying EILs to crop production, but it does not take into account the inherent lag time between noticing a pest population pressure that will cause economic loss and taking measures to prevent loss. Because often control measures and the machinery to apply them are not readily available, it may take a week or more for control tactics to be initiated after it has been determined that the EIL has been reached. Thus, for IPM to be successful, pest populations must be managed prior to reaching the EIL.

Stern et al. (1959) addressed this problem by devising the concept of economic threshold (ET). Stern et al. (1959) define ET as the population density at which control measures should be initiated to prevent an increasing pest population from reaching or exceeding the EIL. The use of ETs and EILs are requirements of successful IPM practices, because IPM is often reactionary (based on thresholds) rather than preventative in nature (Pedigo et al. 1986). However, ETs and EILs are useless without comprehensive scouting practices and reliable information defining where the ET and EIL reside for different crops at different growth stages in different growing conditions with different insect pests (Wright et al. 1987; Hutchins et al. 1988; Higley and Pedigo 1996; Culy 2001). Moreover, as the world has become more connected, new invasive pests have emerged, pest species have evolved different life histories, control tactics have caused resistance, global changes in weather patterns and the price for commodities (the "V" which determines thresholds) has become volatile. Given the great need for IPM and the many faceted challenges, an exhaustive review is not possible. However, we hope to provide examples of the challenges so that researchers and practitioners can be vigilant in developing and refining IPM to meet the world's needs for sustainable agricultural production.

10.2. Feeding guilds

Because of the variety of crops produced worldwide under different growing conditions and with different potential pests, developing species-specific and region-specific EILs for every species is impossible at least in the short-term. A possible alternative to defining ETs and EILs for each species of insect is to group all species of insects that inflict similar damage and cause similar physiological plant responses into "feeding guilds". In this way, ETs and EILs need only be devised for each guild, not for each insect species (Higley and Pedigo 1996).

Most information available to producers defines thresholds based on average numbers of insects per plant. However, making use of feeding guilds in threshold development and utilization necessitates a different method of quantifying injury because the insect per plant density for one species may not cause the same amount of injury as that same density for another species of insect. For example, 10 flea beetles (Chrysomelidae) per leaf will cause little injury in the absence of plant disease, whereas 10 grasshoppers (Acrididae) will completely defoliate the leaf in a short period. An alternative method that shows promise is the use of injury equivalents (Wright et al. 1987; Hutchins et al. 1988; Higley and Pedigo 1996; Culy 2001). For chewing insects, instead of using number of insects per plant for threshold decision levels, percent defoliation can be used as the unit of injury, making it possible to evaluate the injury of several insect species at the same time.

ETLs and EILs are both based on injury and damage inflicted on the host plant, but not all forms of injury or damage are the same. Boote (1981) classified pest injury into eight classes, six of which can be applied to insect pests: stand reducers, leaf mass consumers, assimilate removers, turgor reducers, fruit feeders, and architecture modifiers. Thus, four of the classes can be used to describe injury and damage by insects on a broad range of crops where the plant leaves are not the product that will be sold (e.g. corn, potato, yam, cassava, rice, wheat). The feeding types applicable to these crops are stand reducers, leaf-mass consumers (defoliators), assimilate sappers, and turgor reducers.

The stand reducers produce an immediate loss in biomass and decreased photosynthesis in the crop (Pedigo et al. 1986). Stand reducers cut a plant's stem and may kill the entire plant. The effects to total yield reduction are influenced by quality and quantity of plants lost throughout the field.

Foliage consumers can also be called defoliators because they consume the leaves of a plant while leaving the stems. It is generally believed that leaf-mass consumption directly affects the absolute photosynthesis of the canopy, however, often has little or no effect on photosynthetic rates of the unit area of the injured leaf tissue (Pedigo et al. 1986). The effect of this type of injury on host plant physiology can be measured by the leaf-mass consumed per unit land area, vertical distribution of the defoliation and timing of leaf consumption (Pedigo et al. 1986).

The assimilate sappers are piercing-sucking insects such as aphids (Aphididae), leafhoppers (Cicadellidae), and rasping insects such as thrips (Thysanoptera). These insects remove plant nutrients after the carbon is taken up by the plant, but before the plant can convert the carbon to tissue (Pedigo et al. 1986).

Turgor reducers can cause injury by girdling the plant stem or boring into the stem. Both of these feeding practices act to influence plant water and nutrient balance. In potato, this group includes insects like *Ostrinia nubilalis* (Hubner) (the European corn borer) (Ziems 2002).

The construction of feeding guilds, ETs, and EILs based on injury equivalents work best for defoliator feeding guilds. Most insect defoliators produce very similar physiological responses in host plants (Poston et al. 1976; Welter, 1989; Higley, 1992; Peterson et al. 1992; Peterson et al. 1996). Although exceptions exist, for example the Mexican bean beetle (*Epilachna varivestis* Mulsant) alters the photosynthetic rates of remaining injured leaf tissue (Peterson et al. 1996). The physiological response of plant hosts to the injury inflicted by piercing/sucking insects is much less clear (Pedigo et al. 1986). It is also important to recognize that an insect's ability to vector viruses or other diseases may make placing a particular insect pest into a feeding guild unrealistic, even if that pest's feeding causes plant responses similar to those caused by other pests (Pedigo et al. 1986).

10.3. Plant response to herbivory

In plants, including those used by humans, growth and development of the crop (biomass production) relates directly to the amount of solar radiation absorbed. The proportion of this biomass that is allocated to the reproductive structures or stored in tubers directly determines marketable yield (Higley 1992). As a consequence, the amount of absorbed radiation determines the productivity of a crop.

Leaves are the primary structures that intercept solar radiation and when leaf tissue is removed, the reduction in light interception is the principle reason of yield losses (Higley 1992). These observations regarding light interception and yield have led to the development of a hypothesis that expects a nearly linear relationship between reduction in light interception and yield loss following defoliation for a variety of crops (Johnson 1987; Waggoner and Berger 1987; Higley 1992).

Many papers in the litreature support the defoliation-light interception hypothesis in soybean and other crops (Higley 1992; Hunt et al. 1994; Haile et al. 1998a, b; Hammond et al. 2000; Peterson and Higley 2001). The leaf area index (LAI) is a ratio of the amount of leaves per unit area of land and ranges from 0 (no leaves present (e.g. start of the growing season) to complete coverage by a full canopy where there are proportionately many more leaves than the land area that they cover (LAI > 5.0). Measuring the LAI of a crop can be a useful tool when used in conjunction with the defoliation-light interception hypothesis. Most crop varieties achieve a LAI between 5 and 6, but maximum light interception (>90%) occurs at an LAI, 4. Expanding on this, maximum light interception should occur until a healthy canopy is defoliated to 20-30% of the maximum LAI. Assuming a tolerant response curve in a crop, this leads to the hypothesis that the critical point (EIL) in the tolerant response curve lies between 20 and 30% canopy defoliation.

Because defoliation damage is common and relatively easy to quantify, it is the most likely candidate for IPM implementation. In addition, the compounding effects of virus transmission are not of concern, although secondary infections of damaged leaves may occur. Once the feeding guilds have been established, the host reaction to defoliation in relation to yield must be examined. Poston (1983) suggests that host plants will show one of three general patterns: a susceptive response, a tolerant response, or an over compensatory response to defoliation events. If the plant exhibits a susceptive response to defoliation, the damage-injury relationship is linear; thus, for every increment of injury inflicted on the host there is a corresponding incremental yield loss. This response is reported often in the litreature, but in most cases the response to injury is only a susceptive response over the range of injury being studied (Poston 1983). Tolerant responses to defoliation are characterized as having a sigmoidal relationship between yield and injury. Tolerant plants will tolerate or compensate up to specific amount of injury without any corresponding production loss until an optimum stage is reached. After this point, the relationship is linear (like the susceptive response) until a lower plateau is reached. The lower plateau begins at the point after which additional injury to the host does not correspond to a yield reduction (Poston 1983). This type of response is probably the most often observed response to defoliation in nature because most plants possess 'extra' leaf area that is not required for maximum light interception and photosynthetic saturation or maximum yield (Hutchins et al. 1987; Higley and Pedigo 1996; Peterson and Higley 2001).

The over compensatory response shows a relationship much like the tolerant response except at low levels of injury; the host is stimulated to regrow leaf materials, or to increase photosynthetic efficiency of remaining tissues resulting in increased yield. At higher levels of injury this response takes on the appearance and attributes of the tolerant response (Poston 1983).

A complicating factor in developing injury guilds for a crop species is the effect of injury timing on plant yield. Typically, early season defoliation results in greater yield loss than later season when a plant has a full canopy. Yield response is also affected by the plant reproductive status as many crops have been found to be more sensitive to injury during the flowering stage. As an example of the effects of timing on guild EIL development, we examine the development of EIL in potato crops.

10.3.1. Defoliator EILs in potato

Throughout the development of EIL for potato defoliators, studies focused on a particular insect in a specific region with little regard for the stage at which injury occurred (Sparks and Woodbury 1967; Hare 1980; Cranshaw and Radcliffe 1980; Wellik et al. 1981; Ferro et al. 1983; Shields and Wyman 1984; Zehnder and Evanylo 1989; Dripps and Smilowitz 1989; Senanyake and Holliday 1990; Senanayake et al. 1993). In 1967, Sparks and Woodbury authored one of the first extension publications to characterize the growth stages of potato. They also made the observation that similar amounts of defoliation at different growth stages caused differing effects on yield with yield being most strongly affected at or around the full bloom stage. Other publications built on this observation when defining EILs for potato.

Yield data exist which show that severe defoliation early or late in the potato life-cycle by Colorado potato beetles had a minimal effect on yield in Manitoba, but defoliation at other stages in the potato life cycle caused a reduction in yield that exceeded 35% (Hare 1980). This publication does little more than validate the work completed by Sparks and Woodbury (1967) 23 years earlier. In fact, almost every study published since Sparks and Woodbury (1967) shows this general trend even though the actual levels of defoliation used to define EILs in each study are different (Cranshaw and Radcliffe 1980; Wellik et al. 1981; Ferro et al. 1983; Shields and Wyman 1984; Zehnder and Evanylo 1989; Dripps and Smilowitz 1989; Zehnder et al. 1995). This information causes problems for producers who are interested in implementing IPM but who are adverse to risk.

Some studies suggest that when defoliated early in the season, plants can compensate for lost leaf area between 10 and 33% (Cranshaw and Radcliffe 1980). Mechanically induced defoliation designed to simulate temporary damage produce similar results (Cranshaw and Radcliffe 1980; Shields and Wyman 1984). Conversely, it was found that season-long defoliation for Manitoba potato fields with low density Colorado potato beetle resulted in significant yield loss and a subsequent lower EIL at first bloom (Senanayake and Holliday 1990) resulting in EILs that are much lower than decision levels for other regions.

All varieties of crops partition nutrients to stems, leaves, roots, and reproductive structures. Early in the growing season, the vast majority of nutrients are partitioned to the stems and leaves of the plant for canopy growth. Later in the growing season, nutrient partitioning is shifted so that reproductive structures (fruits) or storage (tubers) is the primary deposition of nutrients by the plant. Plant varieties may also have an influence and broadly, varieties can be classified as indeterminate or determinate. Indeterminate varieties begin partitioning nutrients to the reproductive or storage structures later and in smaller proportions of total photosynthetic nutrients than determinate varieties. As a result, indeterminate varieties consistently have a larger and more robust canopy while determinate varieties consistently have fruits or tubers with higher dry-matter concentrations than indeterminate varieties.

10.3.2. Conflict in EILs

A growing body of litreature on EILs, pests, and crops grown in different regions, has created more controversy than clarity for growers who wish to adopt IPM. The litreature contains numerous papers that present conflicting conclusions. For example, there are several papers available that discuss the photosynthetic response of the plant canopy to defoliation. Most of the early litreature suggests that insect defoliation causes a reduction in photosynthetic rates of the remaining leaf area (Aldefer and Eagles 1976; Hall and Ferree 1976; Detling et al. 1979; Ingram et al. 1981; Li and Proctor 1984). Most of the more recent litreature suggests that in a number of crops there is no effect of insect defoliation on photosynthetic rates of remaining leaf tissue (Peterson et al. 1992; Peterson and Higley 1996; Peterson et al. 1996; Burkness et al. 1999). There is also at least one paper that suggests that the removal of either partial or entire leaves via insect defoliation increases photosynthetic rates of the plant's left-over leaf tissue because of overcompensation of the remaining leaf tissue (Welter 1989). The conflicting evidences these papers present are most likely a result of utilizing different methodologies; however, considerations of crop variety, growing conditions, region-specific pest attributes must be made.

Solving these problems requires focused research using similar methodology of the experiments that mimics the life history and feeding characteristics of potential pests. With the exception of swarming insects such as locusts, a high level of insect defoliation in the field does not happen in a single day. Thus, in order to accurately define an EIL for insect injury, researchers must mimic the feeding of the defoliator. Most insects defoliate less at the beginning of an infestation and feed progressively more as the development of the insect proceeds from small instars to larger, more destructive instars through molting (Peterson and Higley 2001). Burkness et al. (1998) determined that one-time defoliation of cucumber seedlings had less of an effect on cucumber yield than continuous simulated defoliation (Buntin 2001). Ostlie (1984) found that simulated defoliation conducted in a single day caused less of a yield response in soybean when compared to the same amount of defoliation induced over 12 days. In light of this, some published studies that utilized one-day defoliation methods are inadequate to define EILs and are best suited to model yield loss as a result of weather such as hail (Cranshaw and Radcliffe 1980; Shields and Wyman 1984; Burke et al. 1998).

Methods that characterize the feeding behavior of various insects and use experimentally determined leaf consumption models to dictate daily defoliation amounts are more realistic (Ostlie 1984; Higley and Pedigo 1996). Although, Buntin (2001) found that equal daily defoliation amounts that additively reach the desired end defoliation amount are adequate and are an improvement over one-day defoliation events.

10.4. Challenges to IPM in a changing world

Adoption of IPM will continue to be challenging because of altered growing conditions as a result of human-induced climate change. These changes are a result of increases in carbon dioxide that cause increases in annual temperatures and alteration of rainfall patterns. In addition, increased CO_2 alters plant characteristics while changes in temperatures can result in additional generations of pest species and may alter the interactions of pest species and natural enemies. Global climate change along with globalization also increases the likelihood of introduction and establishment of new exotic pests. Finally, the global market coupled with unpredictable weather patterns will cause rapid changes in the value of crops which is the main determinant of treatment thresholds. Indeed, as a result of projected climate changes, agricultural productivity is expected to decrease by as much as 20% in Africa, Asia, and Latin America with under developed countries facing the most deteriorating effects (IPCC 2007), placing even greater pressures on IPM adoption.

Global changes will affect IPM programs and are likely to alter established thresholds and current practices. Because insects often develop more rapidly at higher temperatures with populations increase at higher rates that causes crop damage more rapidly than current IPM models predict. Insects may have multiple generations per growing season and changes in temperature are likely to favor these insects by increasing their numbers and population growth rates (Bale et al.2002). Thus, treatment decisions based on the number of insects per plant will likely need adjustment to avoid unacceptable losses in yield. IPM programs that incorporate degree days (the accumulated physiological age of insects that grow more rapidly in response to temperatures above developmental minimums) may be less-affected. However, increasing may eliminate frosts in some areas, allowing resident pest species to breed continuously. In addition, elimination of frost may allow subtropical species to establish changing the ecology of natural and managed ecosystems. In addition, changing temperatures can also affect biological control agents.

Consistent and continuous increases in temperature have been observed to reduce the effectiveness of both insect pathogens (Stacy and Fellows 2002) and parasitoids (Hance et al. 2007). Differential effects of temperature on parasitoid and host populations can also result in temporal and spatial separation, reducing effectiveness of these biological control organisms (Ris et al. 2004).

10.4.1. Response of pests to IPM

The Western corn rootworm, *Diabrotica virgifera vigifera* LeConte, offers a case study in the challenges to IPM. This insect has an exceptional ability to adapt and change towards a variety of management strategies (Gray et al. 2009). Historically the western corn rootworm is believed to have originated in Central America where they have been pests of maize (*Zea mays* L.) for about 5000 years (Melhus et al. 1954). The larvae of this pest cause economic losses plus money spent on control at estimated costs of $1 billion annually in the United States (Mitchell et al. 2004) and now it is a pest in Europe and the global estimate exceeds $1 billion (Kaster and Grey 2005, Kiss et al. 2005). Larvae of this pest feed on the roots of a number of grasses and maize (Branson and Ortman 1967, 1970; Clark and Hibbard 2004, Oyediran et al. 2004). It has been reported that the first adaptive change of this pest may have occurred when the Spanish introduced monoculture to Central America. Large areas of monoculture were a big change from the scattered small fields of the small producers that was planted amongst grasses and cucurbits (Branson and Krysan 1981). The western corn rootworm was reported a pest in the western portion of the United States as early as 1867 and then another change occurred with expansion eastward across the Corn Belt (Chaing 1973; LeConte 1868-1869). Maize was grown in monoculture in areas that presumably were supporting low populations of western corn rootworm on grasses, but in the absence in maize (Branson and Ortman 1967; Branson and Ortman 1970; Clark and Hibbard 2004). Reports of this insect pest of maize were on Sweetcorn in Colorado (Gillette 1912). With an increased production of maize, the western corn rootworm continued its expansion eastward and in 1929 it was reported in Nebraska (Tate and Bare 1946) and then Chaing (1973) reported it had expanded and become a pest across most maize production areas of Midwestern United States.

With increased maize production areas, increased monoculture and the introduction of insecticides, the western corn rootworm exhibited another change. Ineffective control of rootworm by insecticides were reported to be observed in 1959 and documented by Ball and Weekman (1963). Areas infested with western corn rootworm were treated with organochlorine insecticides continued to grow until a near crisis occurred. By 1980 nearly the entire Corn Belt had insecticide resistant populations of rootworms (Metcalf 1986). The use of cultural control, by farming practices such as crop rotation has been used as an effective IPM strategy. Soybeans or other non-host crops are a recommended strategy for use for control of the western corn rootworm (Chaing 1973).

The next adaptation or change in western corn rootworm population was selection for survival on the soybean-maize rotation that was reported in 1987 and documented by Levine et al. (1996) and Levine et al. (2002). The extend of rotation-resistant populations of western corn rootworm and the loss of ovipositional fidelity to maize has negated the advantages of crop rotation (Grey et al. 2009). The agricultural landscape of maize-soybean rotation is credited with selecting a variant of the western corn rootworm capable of surviving on both crops. Grey et al. (2009) have reported that the western corn rootworm has continuously adapted the pest management strategies and they give the examples of resistance to conventional insecticides and crop rotation. Transgenic maize crops were produced with insecticidal toxins from the bacterium *Bacillus thuringiensis* (Bt) and because the western corn rootworm has shown the ability to circumvent several management strategies; concern was expressed for the development of engineered maize with resistance to western corn rootworm (Tabashnik et al. 2004; Tabashnik et al. 2008). In 2003, Bt maize was commercially released against the target of the western corn rootworm. The strategy used in the United States to delay resistance to transgenic crops is the refuge strategy. However, Gassman et al. (2011) stated the first example of evolved resistance in the western corn root worm against *Bt* toxin. Clearly, the western corn rootworm has developed tremendous capacity to adapt to maize production practices, starting with the shift from native grasses to maize in monoculture, then the pest status as maize production increased across the United States, this was followed by adaptation and development of resistant populations to multiple insecticides followed by an invasiveness to the soybean-maize crop rotation practices. The last and most recent adaptation of resistance to Bt maize (Cullen et al. 2013).

10.4.2. Unintended consequences of genetically modified organisms

The role of IPM and the integration of insect-resistant genetically modified (GM) or (GMO) crops into management strategies and the potential effects on non-target organisms has been discussed by O'Callaghan et al.(2005). Extensive research has been conducted to address the impacts of introduction of GMO plants as a strategy for addressing major insect pests of crop plants (Kennedy 2008). Also, the present and future role of GMO maize in IPM systems has been reported by Hellmich et al. 2008. There have been both intended consequences and unintended consequences in both conventional breeding of crops and genetically modified crops (Cellini et al. 2004). Much concern has focused on environmental and human safety with focused attention to integrated pest management(IPM) developed as a strategy to deal with insecticide failure and now a second strategy which utilizes GMO crops with some of same concerns for environment and human safety (Romeis et al. 2008). It should be noted that both the use of insecticides and GMO's violate a basic concept in IPM and that is one of monitoring and integration of strategies only use after a pest has reached an EIL.

10.4.3. GMO and IPM

Because GMO are used regardless of pest pressure, they strongly select for resistance even when pest densities are below EILs. When one uses GMO plants as a strategy for management of insect plants, then one weighs the possibilities that pest protection may be being purchased even in the absence of the pest. Currently, insect protection is being purchased without regard to economics, environmental safety and Insect Resistance Management (IRM) (Hellmich et al. 2008). A strong environmental concern is the possible adverse effects of GMO's on non-target plant feeding species, natural enemies, and beneficial insects such as pollinators (O'Callaghan et al. 2005)

10.4.4. IPM challenges in Pakistan

Despite the fact that Integrated Pest Management (IPM) has been applied in several crops in Pakistan, the transfer of this approach remained a bottleneck. Due to diversity in Pakistan, monoculture and strip cropping systems are common. The pest population problems and outbreaks are more in monocultures than in mixed cropping systems. This has led to overwhelming use of chemical pesticides.

Cotton crop in Pakistan is vulnerable to many kinds of insect pests and mites which cause 20-40% losses in this crop. Approximately, 46000 tons of pesticides were used during the year 2000, of which 60% of the pesticide was use in cotton. This high use of chemicals has resulted in resistance to many pests to these chemicals, health issues and residues in food chain (Mallah and Korejo 2007). Depending heavily on chemicals for pest management has also resulted in several socio-economic problems. Creating monocultures and depending only on chemicals for controlling pests along with zero tillage practices have facilitated the use of modern farming system to produce more. However, using natural enemies as control methods for pest population is not the primary control methods used by the farmers in Pakistan.

Relying only on one control strategy of pest management is not sufficient to overcome the losses. Rather, a broad ecological attack is needed in which several controlling methods work together to control and manage pest populations. Integrated Pest Management (IPM) is a decision based system keeping in view the cost/benefit, its impact on society, producers and on environment (Marcos 1998). IPM technique works collectively using cultural, biological, chemical methods as well as resistant and tolerant varieties (Sarwar 2004). Furthermore, it also reduces the hazards related to pests and pest management techniques (Thomas 2009). Integrated pest management is not only helpful in increasing productivity and sustainability but also reduces the non-judicious use of pesticides in developing countries (Systemwide 2010). Using IPM technique, a 70% decrease in the pesticide use while 42% increase in yield has been reported (Pretty 2006). To safe guard the non-target organisms and environment, it is critical to have knowledge about the correlation between crops, pests and environment.

Lack of knowledge about IPM, information, operative difficulties, higher costs and risks, intensive labor and time, quantity and quality of yield also contribute to limited adoption of IPM technology (Alston and Reding 1998).

Pakistan lacks the true enforcement of regulations for a sustainable crop production. The regulatory body, Pakistan Environmental Protection Agency (Pak-EPA) has the responsibility to promote research and development of science and technology, identifies the needs and provides information and guidance to public for the sustainable development. The regulatory bodies also ensure safety for consumers and environment by agricultural commodities, use of agrochemicals and by genetically engineered crops. These all measurements are meant to improve the quality and quantity of food produced. The commercialization of any chemical involves high cost thus enabling agrochemical industry to invest more and utilization of the available resources wisely (CropLife, 2003). However, in Pakistan, due to small agrochemicals industry, there is a lack of company owned stewardship of the products. Majority of the used agrochemicals are based on old chemistry which are more damaging to humane health and environment. With the development of export market and increase in profit margins, it is important to address and enforce regulations for pesticide use and policies that will favor IPM.

Financial constraint is the major one among many other limiting factors in achieving any developmental objectives. Pakistan like any other developing country also lacks the funding for Integrated Pest Management (IPM) development and deployment. The agriculture research and extension work thus is affected directly due to low funding. Furthermore, to keep the IPM community updated with the recent findings and improvements within and outside the country, it is important to have strong communication structure. Print and electronic media play a key role to disseminate the desired information to stockholders. Developed countries are well equipped with facilities of telecommunication and media to share the knowledge and information. However, developing countries like Pakistan has not only the poor availability but also poor reliability of the limited communication sources. The big cites more often have such of the facilities but remote areas don't have. The researchers and extensionists are working in areas like Pakistan, where 70% of its population is engaged in agriculture, they lack the fundamental facilities. Internet facilities will prove to be very useful for IPM accessing various databases or through Global IPM facility. Thus, Government needs to address and provide this weakly telecommunication aspect of IPM. The socio-economic position of the farmers is another important aspect that needs attention. Off-farm working in farmers to improve their livelihood results in poor agricultural practices and labor shortage as well.

Public sector agricultural research and extension is not up to mark in Pakistan due to lack of facilities, and operational funds. This scenario causes the capable scientists to work in private sector or to move abroad for better opportunities. Several international agencies invest their funding through projects but due to limited time period for these projects create hindrance in characterizing, identifying and testing the IPM. Gender imbalance is also of importance especially when women are actively involved in crop management (Bruin and Meerman 2001).

Developing countries own 60% of its population engaged in off-farm employment in agriculture (Bongaarts, 2002). Particularly when male young adults in a family prefer working in urban areas that results in the old and female agriculture work force behind (Pingali 2001).

Conservation and elevation along with effectiveness of the natural enemies requires a long-term planning. The local prevalence and diversity in predators could be increased with increased habitat diversity that will be useful for biological control of pests. The protection and maintenance of natural enemy has been found critical and difficult especially in their native ecosystems. Modification in pesticide use in a way that requires application only when needed can also be helpful in conservation. Similarly, changing active ingredients, application rates and formulations may also help in conserving the natural enemies. Judicious use of pesticide can increase the use of biological control in any IPM system. In case where key pests are not manageable through biological, cultural or host plant resistance then relying on chemicals are essential to achieve goals of IPM (Sarwar 2012).

An estimated 26-40% loss in yield of food and cash crops has been reported around the globe (Oerke 2006). A 30 % in pre-harvest losses due to insects, weeds and pathogens while 10-20% post-harvest losses have been reported due to insects and rodents (Oerke 2006). The current world food problems and increase in the population do not allow such losses.

Major goal of IPM is to keep pest populations below threshold using beneficial control agents and lesser use of chemicals. Use of chemicals if necessary must be in a way that will cause least amount of harm to beneficial arthropods.

Growth stage is another important factor in IPM. For instance, injury during reproductive stage is more detrimental than at vegetative stage of plant. Thus, recognition of developmental stages is very important for growers and IPM practitioners. This is also important because growth stage of plants determines the response of insects and that economic threshold are also dependent on growth stages.

Majority of the farmers in Pakistan are unable to identify the insect pests correctly. The correct identification of insects is very crucial before implementing any sort of control measures. Field crop pests are generally classified based on type of injury they cause. Certain types of the insects consume leaf tissues, hence termed as defoliators. Examples include beetle, caterpillar and grasshopper. Insect pests like corn ear worm, *Helicoverpa zea* (Boddie) constitute the pod feeders group while stem feeder insects feed on stem (hopper). The injury caused by these groups reduce yield significantly. Besides these pests, there are numerous other pests which are not major pests like mites, maggots and grasshoppers but need attention from researchers and IPM practitioners.

Measuring the injury level requires proper sampling that depends on type of insect and growth stage of plant. For the accurate count of insects, most of the IPM program use ground or shake cloth or sweep net methods at the time when plant attains sufficient size. The measurement of injury is done more often by estimating the defoliation levels, percent injury of the pod or percentage in the reduction of stand. Plant injury and insect sampling is helpful identifying the potential pests.

Integration of various disciplines is an important philosophy under IPM umbrella (diseases, weeds, and nematodes). Another barrier to the full integration of or implementing the IPM is the lack of an understanding of the type of injury and plant reaction towards that injury. Determining that injury from an insect pest, disease and weed might possibly affect the physiology of the plant that further go far in development the truly integrated approaches to pest management. Now, the researchers have been begun to understand the various types of injuries, their causal organisms and their interaction to find out the impact of injury from all pests on the plants' physiology, so that the unified approaches to the pest management can be established. System of IPM has demonstrated high impact on crop productivity and great adaptability in their application.

The FAO-EU Regional Project in Pakistan proved very useful for extension field workers of Agricultural Extension Department and farmers through IPM-FFS program to grow ecofriendly cotton crop. The FAO-EU funded cotton IPM program suits into the ground realties of the Pakistan and genuine interest to introduce agro ecological sound IPM practices. This program resulted in strengthening farming community and environmentally safe agriculture. Farmer field schools (FFS) also strengthened the knowledge of farmers. This knowledge has resulted in the less use of pesticides and with more production and profitability (Godtland et al. 2004). The FFS is a training model developed primarily by FAO in which farmers gain the decision-making power regarding use of agrochemicals at their field. This unique extension approach is action-learning oriented where farmers are allowed to observe, analyze and make alternative decision about their crops (FAO 2004). Conventional farmers usually do not follow the right criterion and do not consider alternatives to chemical use. These practices and conventional agriculture where pesticides are the major component used has resulted in health hazards, environment degradation, food quality issues and damage to soil structure (Country report 2002). In this scenario, Government should take steps and collaborate with international agencies to promote IPM (Dasgupta et al. 2007).

10.5. Global challenges to IPM

Adoption of IPM will continue to be challenging because of altered growing conditions as a result of human-induced climate change. These changes are a result of increases in carbon dioxide that cause increases in annual temperatures and alteration of rainfall patterns. In addition, increased CO_2 alters plant characteristics while changes in temperatures can result in additional generations of pest species and may alter the interactions of pest species and natural enemies. Global climate change along with globalization also increases the likelihood of introduction and establishment of new exotic pests. Finally, the global market coupled with unpredictable weather patterns will cause rapid changes in the value of crops which is the main determinant of treatment thresholds. Indeed, as a result of projected climate changes, agricultural productivity is expected to decrease by as much as 20% in Africa, Asia, and Latin America with less developed countries facing the most-negative effects (IPCC 2007), placing even greater pressures on IPM adoption.

Global changes will affect IPM programs and are likely to alter established thresholds and current practices. Because insects often develop more rapidly at higher temperatures, populations will increase more rapidly and crop damage may occur more rapidly than current IPM models predict. Insects may have multiple generations per growing season and changes in temperature are likely to favor these insects by increasing their numbers and population growth rates (Bale et al. 2002). Thus, treatment decisions based on the number of insects per plant will likely need adjustment to avoid unacceptable losses in yield. IPM programs that incorporate degree days (the accumulated physiological age of insects that grow more rapidly in response to temperatures above developmental minimums) may be less-affected. However, increasing may eliminate frosts in some areas, allowing resident pest species to breed continuously. In addition, elimination of frost may allow subtropical species to establish changing the ecology of natural and managed ecosystems. In addition, changing temperatures can also affect biological control agents.

Continuous and constant increases in temperature have been observed to reduce the effectiveness of both insect pathogens (Stacy and Fellows 2002) and parasitoids (Hance et al. 2007). Differential effects of temperature on parasitoid and host populations can also result in temporal and spatial separation, reducing effectiveness of these biological control organisms (Ris et al. 2004).

10.6. Recommendations and management

The conclusions drawn from several studies of IPM can be used to suggest recommendations for the adoption of IPM technology at farm level. Some recommendations have been suggested below to boost the adoption of IPM technology.

1) The adoption of IPM technique can be accelerated promoting the cultivars which are insect resistance (Hussain et al. 2011). The host plant resistance is another non chemical and environmental friendly way to avoid pest populations (Sarwar 2011). This would also apply on the harvested grain where insect pests also cause significant damage (Ali et al. 2011).
2) Cultural practices and tactics could have used to support IPM. Controlling the planting dates could result managing the overwintering pests like beetles and caterpillars.
3) Tillage modifications can have left crop residues about 30 % in the field that can further help to change the habitat for pest population dynamics.
4) Other strategies will make more use of cultural practices like cover crops, trap crops, resistant cultivars, and other cultural practices, which the grower might employ specifically for pest management.
5) Use of predators, parasites and pathogens is an effective way to reduce pest populations (Sarwar 2012).
6) Education plays an effective role in the adoption of IPM technology. Hence, it is recommended that government may take actions to upgrade the education as well as training programs for crop producers.
7) Elder farmers do not adopt the innovative technologies like IPM. Hence, it is suggested that government may mediate to create awareness about IPM technology among elder farmers. Incentives should be given to young farmers in crop production.

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Glossary

Acoustic communication: It is a way of inter- or intra-specific communication technique of sending and receiving messages in form of sound.

Agroecosystem: Spatially and functionally coherent unit of agricultural activity where biotic (animals, plants and micro-organisms) interact with abiotic (environmental) elements around them and which is largely created and maintained to satisfy a human want or need. It is not self-sustained, has less and specific biodiversity and exhibits mostly monoculture.

Allatostatins: The term "allatostatins" describes those allatostatic neuropeptides which inhibit the biosynthesis of juvenile hormone by carpora allata.

Allatotropins: These are neoropeptides which stimulate the corpora allata to produce JH.

Allelochemicals: Allelochemicals are interspecific semiochemicals which elicit chemical-signals based communication in some members of different species.

Allomones: Allomones are those interspecific semiochemicals which mediate chemical communication between emitter and receiver specifically providing adaptive advantages and recompenses to the emitter.

Antibiosis: It occurs when the physiochemical qualities of the plants cause decrease in life history such as survival, egg laying capacity reproduction and developmental rates of the arthropods.

Antidiuretic brain hormones: The antidiuretic hormones are diuresis controlling antagonistic hormones which inhibit water loss in insects.

Antixenosis: A mechanism of resistance employed by the host plants that deter the insects from oviposition.

Bacillus sphaericus: A naturally occurring spore-forming gram positive bacterium having strong insecticidal properties.

Bassianolide: A toxin also known as cyclo-octadepsipeptide is secreted by B. bassiana.

Beauvericin: An important toxin isolated from Beauveria, Paecilomyces sp. Samson, the plant pathogenic fungi *Polyporus fumosoroseus* and *Fusarium* spp.

Beauveriolide: A toxin structurally related to bassianolide and beauvericin and isolated from *Beauveria* spp.

Biodiversity: The variety of plants, animals, and microorganisms on planet Earth.

Biointensive IPM (BIPM): A more dynamic and ecologically-informed approach that considers the farm as a part of the agroecosystem and emphasizes the importance of ecological basis of pest infestations.

Biorational Pest management: Biorational pest management involves the substances or processes that execute diminutive or no adverse consequences to the environment and non-target organisms (humans, beneficial fauna and flora etc.); however, impose lethal, suppressive or behavior modifying effects on a target organism and augment the specific control system.

Biotechnology: The effective use of living systems and organisms to develop or make useful products for human beings.

Chemical communication: It is a way of inter- or intra-specific communication technique of sending and receiving messages through chemical cues.

Chitin synthesis inhibitors (CSIs): CSIs belong to that class of biorational insecticides which target polymerization step of chitin-biosynthesis catalyzed by chitin-synthase.

Cytoplasmic resistance: It is conferred by mutable substance (capable or liable to mutation) in cell cytoplasm.

Damage Boundary: It is also called the damage threshold and is the lowest level of injury that can be measured.

Damage: An assessable loss of materials or decrease in their characteristics.

DB: Damage boundary is the lowest level of damage which can be measured on the crop.

Defoliators: Foliage consumers can also be called defoliators because they consume the leaves of a plant while leaving the stems.

Direct pest: They usually attack that part of the plant which is harvested for food.

Eclosion hormone: Eclosion hormone is a neuropeptide which regulates the sequence of events of eclosion (process of adult's emergence from the pupa and nymphs/larvae from egg) in insects.

Eclosion: The emergence of an adult insect from a pupal case or an insect larva from an egg.

Ecological backlash: It is the counter-responses of pest populations or other biotic factors in the environment that diminish the effectiveness of pest management tactics. It includes 3Rs i.e., resistance, resurgence and replacement.

Ecological Pest Management (EPM): EPM is an approach used for increasing the strengths of natural systems to reinforce the natural processes of pest regulation and improve agricultural production. It emphasis on targeting many life stages of pest by pest control and minimizing its survival potential with least possible resources/ways.

Economic Injury Level: It is the lowest population density that will cause economic damage.

Economic Threshold Level (ETL): It is the density of a pest at which a control treatment will provide an economic return. It may also be defined the insect's population level or extent of crop damage at which the value of the crop destroyed exceeds the cost of controlling the pest.

EPN: Entomopathogenic nematodes.

Exuvium: The skin shed after molting.

Frass: The product of the insect's feeding and digestion is termed as frass. For example, sawdust in the excavated holes damaged by powderpost beetle, mud tunnels of termites etc.

Gain Threshold (GT): It can be defined as the amount of damage (=yield loss) to justify management and is calculated by dividing the management costs by the market crop price.

General equilibrium position (GEP): It is the mean pest density over a prolonged period of time during which the pest population vary because of abiotic and biotic factors in constant environmental conditions.

Hopper-burn/Tip-burn: It is marginal chlorosis (yellowing) and necrosis (browning) on injured leaves of mango due to attack of mango hopper.

Indirect pest: They damage those parts of the plant that are usually not harvested for food purpose.

Insect ecology: It is the scientific study of how insects, individually or as a community, interact with the surrounding environment or ecosystem.

Integrated pest management (**IPM**): It, known as integrated pest control (IPC), is an ecosystem-based broad-spectrum strategy that focuses on long-term (sustainable), ecofriendly and economical prevention of pests or their damage by integrating highly compatible pest control techniques such as biological control, habitat manipulation, modification of cultural practices, and use of resistant varieties.

Juvenile hormones: Juvenile hormones (JHs) are neuropeptides that regulate many physiological and metabolic aspects of insect life like diapause, development, reproduction, polyphenisms.

Kairomones: A type of allelochemical compounds produced by plant feeders and are perceived by natural enemies.

Kairomones: Kairomones are those interspecific semiochemicals which stimulate chemical communication between emitter and receiver specifically providing adaptive benefits to the receiver.

Key pests: These are the most serious pests and their GEP lies well above the economic injury level (ETL).

Oligogenic resistance: This type of resistance is also known as “major-gene resistance” and carried by one or more genes.

Persistent pests: These pests can be found on the crops all over the year.

Pest avoidance/exclusion: It is kind of precautionary step which inhibits the entry of any insect pest into any agroecosystem and ensures pest free zone.

Pest monitoring: It is the regular systematic and purposeful observation and recording of pest activities taking place in a specific period and locality/region.

Pest Scouting: It is the process of précised assessing of pest pressure and crop performance to evaluate economic risk from pest infestations as well as to determine the potential effectiveness of pest control interventions.

Pheromone: Pheromones are those intraspecific chemical factors which are excreted out of the body of emitters and trigger social responses in receivers of same species.

Polliferous insects: The insect species which visit the flowers to get pollens and nectar as food and play vital role in pollination of flora e.g., bees

Polygenic resistance: This type of resistance conferred by many genes and each have the resistance effect.

Precision agriculture: Precision agriculture or information-based management of agricultural production systems consists of geo-referenced data collection and provision of relevant information for management planning.

Primary pests: have potential of complete damage and breed in stable solid grains directly at some point during their life cycle.

Primer Pheromones: These pheromones trigger off a series of physiological changes in the receiver without stimulating any immediate change in its behavior.

Prothoracicotropic hormone: Prothoracicotropic hormone (PTTH) is a neuropeptide which triggers prothoracic gland to produce ecdysone (molting hormone).

Regular pest: These pests occur frequently and have a close association with the host crop.

Releaser Pheromones: These pheromones induce instantaneous and reversible change in the behavior of the receiver.

Sclerotization: Hardening of newly developed insect cuticle is called sclerotization. It is controlled by a hormone called Bursicon.

Semiochemicals: These are chemicals which are used for inter- or intra-specific communication and are also called as infochemicals.

Sporadic pests: The population of such pests is not significant and generally below GEP.

Synomones: Synomones are those interspecific semiochemicals which trigger chemical communication between emitter and receiver specifically providing adaptive benefits to both the emitter and receiver.

Tactile communication: It is a way of inter- or intra-specific communication technique of sending and receiving messages through touching or tapping in insects with poor sound perception and vision.

Vegetable: The leafy green, stem, and root or even flower stalk portion of an edible plant.

Wolbachia: A group of intracellular bacteria that comprises species exhibiting parasitic, mutualistic and commensal associations with their hosts.

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