Sustainable Management of Insect-Pests

Ahmad Nawaz, Muhammad Sufyan, Muhammad Dildar Gogi, and Muhammad Wajid Javed

Abstract The conception of 'insect-pests' has ascended from human crop cultivation practice and desire of food security from ubiquitous insects. They are also regarded by some as the main competitors of humans for dominance on the earth. The management of insect-pests is hammered by both biotic and abiotic factors. Sustainable pest management is a two-strand approach which requires complete information about control strategy, pest biology and ecology which helps to determine the most appropriate procedure/method (how), timing (when) and place (where) for effective use of any control technology of any pest. In this context, IPM (Integrated Pest Management), ICM (Integrated Crop Management) and IRM (Integrated resistance Management) can help to reduce crop yield losses while managing insect pests without causing harm to non-target organisms. However, the global implementation of these practices has been slow down due to different factors. Conclusively, integration of non-chemical control methods including new technologies with synthetic insecticides will be a promising option for sustainable insect pest management. This chapter will highlight the issues hampering sustainable insect-pests management and suggest ways to overcome these factors. Furthermore, the potential role of different stakeholders is also discussed which can be integrated for fruitful solutions of common problems of insect pest management. Finally, the integration of different therapeutic tools (IPM, ICM and IRM etc.) is underscored to increase crop production without harming the environment.

Keywords IMP · ICP · IRM · Sustainable management · Pesticides

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M. Farooq, M. Pisante (eds.), *Innovations in Sustainable Agriculture*,
https://doi.org/10.1007/978-3-030-23169-9_10

1 Introduction

Insects belong to phylum arthropoda of kingdom Animalia. They have been evolving from about 350 million years, compared to human beings (2 million years). They are remarkable biological organisms and regarded by some as the main competitors of humans for dominance on the earth. Humans depend on insects in many ways like crop pollination, honey and silk production, organic matter decomposition and carbon recycling, and various other vital ecological roles. Honey bees estimated annual contribution in crop production is US$ 15 billion in the United States alone. Similarly, the total estimated pollination services globally exceed US$200 billion for one hundred crops used directly for human food. In addition, the predators and parasitic wasps controlling other pests often go unrecognized but worth billions of US$ annually (Gullan and Cranston 2014). Therefore, insects are inevitable for human survival on earth. In spite of benefits, insects have been of greatest concerns to human race by causing negative impact on their valuable resources. Among the one million described species of insect pests, more than 10,000 species are involved in food losses and considered as major pests (Dhaliwal et al. 2007). The estimated global annual loss of major crops (cotton, wheat, rice, maize, soyabeen, potatoes) due to insect pests ranges from 7.9% to 15.2% (Dhaliwal et al. 2010). The crop damage percentage increases in developing countries due to the lack of knowledge and availability of new technologies for the management of insect pests.

The insect pest management is an essential part of agriculture to compensate the ever increasing food demands of humans. Therefore, the prime-most objective of all countries is the increase in food production. The annual increase in world population is around 97 million per year. In this way, the world population is likely to grow from 7.6 billion to nearly 10 billion by 2050 and further predicted to be 11.2 billion by the end of this century (UN 2017; Saravi and Shokrzadeh 2011). Similarly, it is predicted by Food and Agricultural Organization the United Nations that to keep pace with the demand of increasing population, the world food production needs to increase by seventy percent. Therefore, the existing agricultural systems are under tremendous pressure of ever increasing global population and its food requirements from the same current resources (Saravi and Shokrzadeh 2011). The pests of agricultural crops are actually the bottlenecks for the increase in world food production and the insect pests are of prime importance. Before the introduction of synthetic chemicals, different sustainable practices (cultural, mechanical, and physical control strategies etc.) were used to manage these insect pests in the process of increasing crop production.

Previously, the agriculture intensification investments were often increasing in external inputs of fertilizers and synthetic chemicals. The toxic residues, pest resistance, secondary pest outbreaks, and pest resurgence are the four major glitches encountered with conventional chemical pesticides. It has been reported that more than 90% of the arthropod species (Sukhoruchenko and Dolzhenko 2008) with resistant populations belong to Lepidoptera (15%), Diptera (35%), Coleoptera (14%), Hemiptera (14%). Similarly, the microbial community is also essential for better yield of crops as reported by Allison and Martiny that microbial organisms are sensitive to nitrogen (N), phosphorus (P), and potassium (K) fertilization (Allison and Martiny 2008). In addition, similar to pesticides the concept of monoculture or clean culture crop cultivation also has negative impact on biodiversity, insect pest natural enemies and other non-target organisms.

In agricultural systems, the basic principle for undesired variables management is similar to other systems, including the human body and social systems. The direct application of a corrective measure for an undesired entity never produces sustainable desired effects. Instead, as a matter of fundamental principle, external counter force application into a system can be effective only for short term relief from the problem. The sustainable and long term solutions should be achieved through restructuring the system. Therefore, the underpinning for pest management approach should be a full composite of innate plant defenses, plant mixtures, soil, pest natural enemies, and other components of the agricultural system. These natural “built in” managers are interconnected and renewable in sustainable manner. The “treat-the-symptoms” approaches like synthetic chemicals and other tactics should be the last option of defense.

The conception of ‘insect pest’ has ascended from human crop cultivation practice and desire of food security from ubiquitous insects. A pest management plan should constantly start with the question “Why is the pest a pest?” and in response, it should seek weaknesses of the cultivation system and poor agronomic practice (s) that allowed organism (s) to stretch pest status and finally address underlying issues to manage that pest (s). However, the global implementation of these practices has been slow down due to lack of knowledge, limited technical capacity, dearth of priority in agriculture sector and low demand by small land holder farmers. The sustainable pest management system enhances those pest management methods that support crop production sustainability and do not pose risk to farmers’ incomes, health and environment. Therefore, the current chapter will discuss the factors affecting insect-pest management and their management. The role of stakeholders including academia, industry, research institutes, farmers, government agencies, etc. regarding legislation of crop production and protection, natural enemies conservation, genetically modified crops management, resistance management etc., is also highlighted. Finally, the chapter will focus the recent investments in crop production which are based on economically sound, socially acceptable, and environment friendly inputs. In this context, IPM, ICM and IRM are considered comprehensive agricultural practices that help to reduce crop yield losses while protecting environment as well as human health.

2 Issues of Sustainable Insect-Pest Management

Insects are ubiquitous in nature and known as most successful animals on planet earth due to several aspects like diversification, high reproductive potential, malleable exoskeleton and metamorphosis etc. The sustainable management of insect pests is quite difficult task due to both biotic and abiotic factors mainly climate change, biodiversity management, misuse of resources, and most importantly the resistance development against pesticides. Following are the major constraints for sustainable management of insect pests.

2.1 Climate Change

The ongoing changes in climatic conditions and regular weather effects can alter development and dispersal of different insect species. It is evident that fluctuations in surrounding temperature regimes are involved in modifications in development rates, insect survival, voltinism and consequently effect the size, density, genetic variability of populations and host plant interactions (Table 1) (Bale et al. 2002). The change in temperature thresholds is also pre-requisite for insect flight and can also vary among insect species, with season as well as with region. Black bean aphid (*Aphis fabae* Scopoli) require different temperatures for wing beating (6.5°C), horizontal flight (13°C), sustained upward flight (15°C) and for take-off (17°C) (Cockbain 1961). There might be both positive and negative reproduction and developmental responses of insects to temperature conditions. Some economically important multivoitine insects like bark beetle (*Ips typographus* L.) can get benefit by an earlier completion of life cycles and establishment of additional generations within a season due to increase in temperature (Jönsson et al. 2009). Increase in temperature frequencies can lead to decreased growth rates and fecundity for the multitude of species. The increased mortality rates are also observed due to increase in temperature. Similar effects (*Operophthera brumata* L., *Epirrita autumnata* Borkhausen and *Lymantria dispar* L.) are possible with decrease in temperature extremes (Moore and Allard 2008). The gradually changing climate scenario is likely to influence distribution and severity of crop pests and diseases (Oerke 2006), impact the sustainability of the crop production and protection system (Lamichhane et al. 2015), complicate the use of reduced-risk-pesticides (Hossard et al. 2014) and ultimately limit global food production (Foley et al. 2011). Climate change may enhance the adaptability of pests in previously detrimental areas (Chakraborty 2013) and accelerate spatio-temporal pest pressure due to resurgence and replacement phenomena (Chakraborty and Newton 2011). Adaption of indigenous and exotic pest species to changing climate, better-adapted pest genotypes, lack of stable and predictable cropping system, resurged impact of pest status and their losses, comprehensive revision in plant health strategies, climate-resilient production and protection system, future legislation to increasingly stringent climate and human-health concerns and augmented pressure on high-yielding cropping system and food-security are the major operational and practical challenges generated by climate change (Lamichhane et al. 2015).

No doubt, temperature is important for survival, growth, development, dispersal and voltinism but other factors like draught and precipitation also share a vital role in insect abundance. Overall, climate transformation might effects population

Table 1 Examples depicting impact of climate change on various life parameters of insects

Insect	Technical name	Climate change associates	Effects and insect associated change	References
Stinkbug in England and Japan	*Acrosternumhilae* (Say)	Temperature increase of only 2 °C	Distribution range shifted to 300 km northward	Trumble and Butler (2009)
Mountain pine beetle in the USA and Canada	*Dendroctonus ponderosae* (Hopkins)	Temperature increase of only 2 °C	Distribution range shifted to 30–400 km northward	Logan and Powell (2001)
European corn borer	*Ostrinia nubilalis* (Hübner)	Temperature variation	Distribution range shifted to maize growing areas which previously free of infestation	Lamichhane et al. (2015)
Codling moth	*Cydia pomonella* (L.)	Temperature variation	Phenological changes occur and formerly univoltine species have become bi- or multivoltine	Stoeckli et al. (2012)
Aphid species	*Myzus ascalonicus* (Doncaster)	Mild change in winter temperature	Survival and colonization patterns of aphids shifted from holocyclic to anholocyclic form	Radcliffe and Ragsdale (2002)
Aphids	*Brachycaudus helichrysi* (Kaltenbach), *Myzus persicae* (Sulzer) and *Sitobion avenae* (Fabricius)	1°C rise in winter Temperature	Radical change in migration phenology by 19 days	Zhou et al. (1995)
Potato psyllid	*Bactericera cockerelli* (Sulc)	Warmer temperature of winter	Previously not establishing species since centuries has migrated, introduced, established and colonized successfully in California	Liu and Trumble (2007)
Poly voltine species of bark beetles	*Ips typographus* (L.)	Temperature increase	Augmented development and reproduction rates, earlier completion of life cycle and establishment of additional generations	Jönsson et al. (2009)

(continued)

Table 1 (continued)

Insect	Technical name	Climate change associates	Effects and insect associated change	References
Brown plant hopper and rice leaf folder	*Nilaparvatha lugens* (Stal) and *Cnaphalocrocismedinalis* (Guen)	Temperature increase	Declined survival rate, alteration in voltinism and changed geographical distribution	Karuppaiah and Sujayanad (2012)
Phloem-feeders, ants, chewing herbivores and parasitoids,	Leaf miner	Elevated level of CO_2	Reduction in abundance of phloem-feeders and ants, while increase in abundance of chewing herbivores and parasitoids,	Hillstrom and Lindroth (2008)
Ichneumonids, Brachonids and Chalcidoids parasitoids	Ichneumonoidea (Latrelle)	Elevated level of O_3	41%, 33% and 26% reduction in abundance of Ichneumonids, Brachonids and Chalcidoids, respectively	
Several butterflies, beetles, dragonflies and grasshoppers	*Carterocephalus palaemon* (Pallas)	Isothermal shift (increase in temperature)	Expansion in their geographical range to higher latitudes and altitudes	Parmesan et al. (1999)
Migratory butterflies in Europe		Isothermal shift (increase in temperature)	≈ 60% of non-migratory butterflies in Europe have extended their geographical distributions by 35–240 km northwards	
Monophagous butterfly	*Boloria titania* (Esper)	Climate changes in term of temperature increase	Incongruity in synchronization and disturbance in trophic interactions between *B. titania* and its larval host plant *Polygonum bistorta*	Schweiger et al. (2008)

(continued)

Table 1 (continued)

Insect	Technical name	Climate change associates	Effects and insect associated change	References
Winter moth	*Operophtera* brumata (L.)	Climate changes in term of temperature increase	Asynchronization in insect-plant and disturbance in their trophic interactions eg. egg hatching (> 90%) before oak (*Quercus robur*) bud burst	Visser and Holleman (2001)
Marsh fritillary butterfly and its parasitoid	*Euphydrias aurinia* (Rottermburg) and *Cotesia bignellii* (Marshal)	Climate change (increase in temperatue)	Decrease in developmental times of the host Alteration in dynamics of host-parasitoid system and synchronization host-parasitoid interactions	Klapwijk et al. (2010)
Herbivore, pollinators, seed-dispersing insects	*Plutella xylostella* (L.) and the generalist predator *Podisus maculiventris* (Say)	Changes in temperature, rainfall patterns and atmospheric concentration of gases	Positive and negative insect-plant interactions; 2–3 fold increase in emission in plant volatile organic compounds (VOCs) (such as methyl jasmonate or methyl salicylate), more fragrant environment, reduction in future herbivory rates and disruption in pollination and seed-dispersal causing reduction in reproduction and fitness of plants	Constable et al. (1999); Penuelas and Staudt (2010)
Parasitoid wasp	*Cotesia marginiventris* (Cresson)	Increasing temperature	Effects on fecundity and 90% reduction of off-spring production	Dukes and Mooney (1999)
Argentine ants	*Linepithema humile* (Mayr)	Increasing temperature	Distribution dissemination to northward and fecundity disruption of more inborn ant species	

(continued)

Table 1 (continued)

Insect	Technical name	Climate change associates	Effects and insect associated change	References
Spruce budworm	*Choristoneura fumiferana* (Clemens)	Increasing temperature	50% increase in fecundity	Régnière (1983)
Moth in Norway birch forests	*Argyresthia retinella* (Zeller)	High temperatures and droughts	Severe outbreak of epizootics	Tenow et al. (1999)
Winter moth	*Operophtera brumata* (L.)	High temperatures	Increased epizootic and range in in Norway birch forests	Hagen et al. (2007)
Pine processionary	*Thaumetopoea pityocampa* (Denis & Schiffermüller)	Warmer winters due to rising temperatures	Epizootics outbreak on Scot pine	Buffo et al. (2007)
Oak dieback disease and ambrosia beetle	*Platypus quercivorus* (Murayama)	Global warming	Increase in range of ambrosia beetle and epidemic outbreak of oak dieback disease in Japan due to encounter of beetle with fungus.	Kamata et al. (2002)
European pine sawfly and shoot beetle	*Neodiprion sertifer* (Geoffroy) and *Tomicus destruens* (Wollaston)	Global warming	Epizootics outbreak and severe damage on pines	Faccoli (2007)

dynamics of insect pests differently in different agro-ecological zones and agro-ecosystems. Therefore, it is obligatory to understand and address these issues through more research on different aspects (metabolic alterations, prediction models, evolutionary changes) of insect pests.

2.2 Insecticide Resistance

The indiscriminate use of pesticides posed a major challenge to the targeted pests by forcing them to either disperse to novel environment and/or adapt newfangled conditions. Such adaptations could be attributed as gene mutation, alteration in population growth rates, and escalation of generations etc., which ultimately cause pest resurgence and pest resistant incidents. Pest resistance can be defined as "Heritable change in the sensitivity of a pest population that is reflected in the repeated failure of a product to achieve the expected level of control when used according to the label recommendation for that pest species" (IRAC 2013). The development of pesticide resistance is a most serious bottleneck in the sustainable pest management because resistant individuals continue to reproduce and eventually become the dominant part of the population with the passage of time. In 2001, the estimated number of resistant insects and mites was around 700 which were calculated 600 by the end of 1990 and this trend is likely to be continued. Pesticide resistance has been reported against a number of insecticide groups. According to Rai and Ingle (2012), a large number of weed species (270), plant pathogens (150) and insect species (more than 500) acquired resistance against herbicides, fungicides and insecticides respectively (Rai and Ingle 2012). There are many insect species who developed resistance against oganochlorine insecticides like cyclodiene (291 species) and DDT (263 species). Similarly resistance has been found in other insecticide groups e.g., 260 species have developed resistance against organophosphates followed by carbamates (85 species), pyrethroids (48 species) and fumigants (12 species) (Dhaliwal et al. 2006). Almost 330 cases of imidacloprid resistance have been reported by APRD (Arthropod Pesticide Resistance Database) followed thiamethoxam (130 cases) and acetamiprid (50 cases) resistance (Bass et al. 2015). The insect pests who showed resistance was mainly white fly (*Bemisia tabaci* Gennadius) followed by the green peach aphid (*Myzus persicae* Sulzer), the cotton aphid (*Aphis gossypii* Glover) and the rice brown plant hopper (*Nilaparvata lugens* Stål). The genetically modified crops with insecticidal toxins from *Bacillus thuringiensis* (Bt) showed resistant against a number of insect pests. But some reports (Tabashnik et al. 2003) showed resistance development in major insect pests like diamondback moth (*Plutella xylostella* L), pink bollworm (*Pectinophora gossypiella* Saunders) and American bollworm (*Helicoverpa armigera* Hübner). Some examples of resistance development in insect pests of economically important crops are given in Table 2. Thus, the issue of insecticide resistance always causes pressure to develop novel compounds to avoid resistant development in insect pests. Therefore, every year around one million insecticidal compounds have been screened out (Resh and Cardé 2009) for better management of insect pests.

2.3 *Pest Resurgence*

Besides resistance development, the pest resurgence is another phenomenon which hampers the efforts of sustainable pest management. Pest resurgence is known to occur due to many reasons (Dhaliwal et al. 2006) but the use of broad spectrum and persistent pesticides is considered as leading cause because of their toxic effect on non-target organism especially the insect natural enemies. In literature, many pesticide-induced pest outbreaks have been reported (Gill and Garg 2014) but brown plant hopper (*Nilaparvata lugens* Stal) outbreak in rice gained major importance. Generally, BPH population was kept under control by different entomophagous insects (mirid bugs, ladybird beetles, spiders) but pesticide exposure destroyed the BHP natural enemies. Pesticides influenced the fecundity of females (Wang et al. 2010) which further enhanced BHP resurgence. The other examples of pest resurgence are bed bug (*Cimex lectularius* Latreille) and cotton bollworm (*Helicoverpa armigera* Hübner) which occur due to indiscriminate use of pesticides and resistance development (Davies et al. 2012; Mironidis et al. 2013).

Table 2 Incidence of insecticide resistance development in insect pests of economically important crops

C. Name	T. Name	Family & order	Insecticide	Crop	Reference
Cotton leaf hopper	*Amrasca devastans* (Dist.)	Hemiptera: Cicadellidae	Neonicotinoids	Cotton	Rabia et al. (2017)
Dusky Cotton Bug	*Oxycarenus byalinipennis* (Costa)	Hemiptera: Lygaeidae	Pyrethroids, organophosphate, spinosad, benzoate, nitenpyram and imidacloprid.	Cotton	Ullah et al. (2016)
Cotton aphid	*Aphis gossypii* (Glover)	Hemiptera: Pseudococcidae	Neonicotinoid (thiamethoxam, acetamiprid and clothianidin)	Cotton	Herron and Wilson (2011)
Cotton Whitefly	*Bemisia tabaci* (Gennadius)	Hemiptera: Aleyrodidae	lambda-cyhalothrin, cypermethrin, deltamethrin fenpropathrin	Cotton	He et al. (2007)
Cowpea Aphid	*Aphis craccivora* (C.L. Koch)	Hemiptera: Aphididae	Malathion, chlorpyrifos, thiamethoxam and carbosulfan	Cowpea and pulses	Kandil et al. (2017)
Cabbage aphid	*Brevicoryne brassicae* (Linnaeus)	Hemiptera: Aphididae	Organophosphate, Neonicotinoids	Cabbage	Ahmad and Akhtar (2013)
Cotton Whitefly	*Bemisia tabaci* (Gennadius)	Hemiptera: aleyrodidae	Acetamiprid	Cotton	Basit et al. (2011)
Mustard Aphid	*Lipaphis erysimi* (Kalt.)	Hemiptera: Aphididae	neemarin	Mustard	Kumar et al. (2007)
Green peach aphid	*Myzus persicae* (Sulzer)	Hemiptera: Pseudococcidae	Pyrethroids, carbametes, organophosphate	Canola and cabbage	Needham and Sawicki (1971)
Spotted bollworm	*Earias vittella* (Fabricius)	Lepidoptera: noctuidae	Organophosphate, pyrethroid and biorational Insecticides	Cotton and okra	Jan et al. (2015)

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Table 2 (continued)

C. Name	T. Name	Family & order	Insecticide	Crop	Reference
Cotton bollworm	*Helicoverpa armigera* (Hübner)	Lepidoptera: noctuidae	Endosulfan and chlorpyriphos	Cotton	Kranthi et al. (2002)
Pink bollworm	*Pectinophora gossypiella* (Saunders)	Lepidoptera: noctuidae	Pyrethroids and endosulfan		
Spotted bollworm	*Earias vittella* (Fabricius)	Lepidoptera: noctuidae	Cypermethrin		
Tobacco caterpillar	*Spodoptera litura* (Fabricius)	Lepidoptera: noctuidae	Chlorpyriphos		
Whitefly	*Bemisia tabaci* (Gennadius)	Hemiptera: aleyrodidae	Cypermethrin		
Cotton mealybug	*Phenacoccus Solenopsis*	Homoptera: pseudococcidae	Bifenthrin	Cotton	Mansoor et al. (2016)
Green peach aphid	*Myzus persicae* (Sulzer)	Hemiptera: Aphididae	Imidacloprid		Nauen and elbert (2003)
Corn earworm	*Helicoverpa zea* (Boddie)	Lepidoptera: noctuidae	Pyrethroids	Maize	SEMINIS (2018)
European corn borer	*Ostrinia nubilalis* (Hubner)	Lepidoptera: crsmbidae	Pyrethroids		
Fall army worm	*Spodoptera frugiperda*	Lepidoptera: noctuidae	Organophosphates or carbamate		
Whitefly	*Bemisia tabaci* (Gennadius)	Hemiptera: aleyrodidae	Neonicotinoid insecticide	Cotton, vegetables, and ornamental crops	Nauen and Denholm (2005)
Colorado potato beetle	*Leptinotarsa decemlineata* (Say)	Coleoptera: chrysomelidae	Neonicotinoid insecticide	Potato	
Army worm	*Spodoptera litura* (Fabricius)	Lepidoptera: noctuidae	Emamectin and Indoxacarb	Multiple crops	Ahmad et al. (2008)
Whitefly (biotype Q)	*Bemisia tabaci* (Gennadius)	Hemiptera: aleyrodidae	Acetamiprid, Imidacloprid, and Thiamethoxam	cotton, vegetables, and ornamental crops	Luo et al. (2010)
Tomato leafminer	*Tuta absoluta* (Meyrick)	Lepidoptera: Gelechiidae	Abamectin	tomator	Lietti et al. (2005)
Anopheles spp.	*Anopheles culicifacies* (Giles)	Diptera: Culicidae	malathion		Raghavendra et al. 1991
Stem borer	*Chilo suppressalis (Walker)*	Lepidoptera: Crambidae	Fipronil	Rice	Li et al. (2007)

2.4 Pesticides Impact on Non-target Organisms

Biological control is an effective strategy for controlling arthropod pests. Natural enemies such as predators, parasitoids and entomopathogens have been utilized for crop pest management for centuries. Today the biological control schemes have been operated successfully across the globe for the management of pests in agriculture, forestry and horticulture. But it is evident that the pesticides severely affect the non-target organisms especially predators, parasitoids, pollinators, earthworms, humans, birds, fishes, amphibians (Gill and Garg 2014). Unfortunately, biological control agents (parasitoids and predators) are most susceptible to negative effects of insecticides. These pesticides are severely affected their viability and efficiency to reduce the pest infestation. There are a number of studies which showed the negative impacts of pesticides on insect natural enemies. Ghananand et al. reported that spraying with cypermethrin and imidacloprid caused higher mortality of insect natural enemies. On the other hand, spraying with bio-pesticides and neem based insecticides were less toxic to coccinellids, braconid wasps and predatory spiders (Ghananand et al. 2011). Similarly, more number of arthropods such as coccinellids was present in non-sprayed fields compared to fields sprayed with insecticides and herbicides to control the insect pests (Amalin et al. 2009). In addition, different pesticides may have different levels of toxic effects on natural enemies. The foliar application of spirotetramat, buprofezin and fipronil were significantly less toxic to insect natural enemies in comparison with imidacloprid, clothianidin, admire, thiamethoxam and acetamiprid (Kumar et al. 2012).

2.5 Biodiversity

Before the introduction of synthetic insecticides in agriculture, the forces of potential creation (biotic potential) of insects and forces of potential destruction (environmental resistance) were playing their roles to maintain a balance (biological equilibrium) among the insect population. The use of chemical insecticides caused a huge imbalance among phytophagous and entomophagous insect diversity. The practice of monoculture for crop production also caused effects on plant diversity similar to insecticides. Recent investigation revealed the negative impacts on the ecosystem biodiversity as well as the biological control of pests (Geiger et al. 2010). Plant biodiversity plays an important role in sustainable pest management. An analysis of 22 case studies dedicated plant diversity services for orchard pest control revealed positive impact on pest control (16 cases) or null (9 cases), but also negative (5 cases) (Simon et al. 2010). The negative impact could be due to many reasons which need further research to identify the processes involved at different levels of natural control. Therefore, the biodiversity management could yield effective control of insect pests on sustainable basis.

The above mentioned issues are the bottlenecks for the sustainable pest management of insect pests in different agro-ecosystems. The climate change impacts can be minimized by adapting innovative technological developments, modifications in farm production practices and financial management. In addition, the government programs and insurance policies are also important. The insecticide resistance and resurgence issues are addressable by integration of different pest control options like reduce risk pesticides, biopesticides, botanical insecticides, pheromones. Furthermore, the use of nanotechnology based nanopesticides also has potential to tackle the issues of pest resistance and resurgence. Similarly, the biodiversity and genetic diversity at farm level can be maintained by practicing zero tillage and conservation agriculture techniques for sustainable pest management of different agricultural insect pests.

3 Pre-requisites of Sustainable Management of Insect Pests

Pest management is a two-strand approach which mainly relies on the knowledge of the strategy, pest biology and pest ecology in agroecosystem. 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; Pedigo and Rice 2009).

The knowledge of various aspects of biology and ecology of pests lays the foundation of an efficient and economical pest control strategy and is important for achieving key objectives of pest management. For examples, such 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 (Norris et al. 2002; Pedigo and Rice 2009).

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 (Knipling 1979; Pedigo and Rice 2009). However, Geier (1966) suggests some supplementary characteristics/elements of sustainable pest management system that a pest management technology/system should be: (1) highly target specific i.e., very selective for pest and safe for non-target 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 (Dhaliwal et al. 2006; Buurma 2008; Pedigo and Rice 2009; Alam 2010; Schowalter 2011).

Effective and sustainable insect pest management also depends on economic decision levels which are mandatory 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 (Knipling 1979; Inayatullah 1995; Alam 2010; Jha 2010).

3.1 Information of Insect Pest Biology

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 is 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? (Knipling 1979; Sorby et al. 2005; Dhaliwal et al. 2006; Pedigo and Rice 2009; Jha 2010)

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 any insect pest. The morphological knowledge of an insect helps to develop an appropriate technology and 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 for light-traps depend on the knowledge of structural components and physiology of compound eyes of insects (Pedigo and Rice 2009) which 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 color. The knowledge about the types of mouthparts of insect pests helps to decide that what type of insecticides should be selected for successful control of insect pests. For example, if the infesting insect pests have sucking type of mouthparts, then, insecticides with systemic and contact action will be the most appropriate selection of insecticides. 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 (Dhaliwal et al. 2006; 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 based on growth and development based hormones, peptides from sting gland of parasitoids and pheromones- having IGR or karomone activity have been discovered and their analogs have been synthesized for commercialization and management of insect pests. The knowledge of spiracle respiration can be helpful in controlling the insect pests with fumigation.

The knowledge of insect metamorphosis and its physiology provides so many useful cues about the weak links of insect growth stages and their activity periods and sites which if targeted can ensure effective management of any pest. Such knowledge can also be useful in synchronizing the timing of application of pest management tactics with weak-link or susceptible growth stage of insect; thus, ultimately would be helpful in reducing blind use and application intensity of pesticide on crop. These facts 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.

Incorporating pest controls at many different stages and limiting pests' abilities in many small ways are the foundation of ecological pest management (Schowalter 2011). Production systems that use ecological principles to imitate nature, along with multiple tactics and the right information, can: (i) synergize individual impacts of strategies when used together, (ii) reduce the risk of crop failure by distributing the burden of crop protection across many tactics, (iii) minimize environmental disruptions and threats to human health, (iv) slow the rate at which pests adapt or evolve resistance to a given management tactic because and reduce operating costs and ultimately improve profitability by minimizing inputs (Dhaliwal et al. 2006; Pedigo and Rice 2009)

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

3.1.1 Egg Laying Behavior

The some insects are endophytic (fruit flies) and some are exophytic (most of the bollworms, borers etc.). 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.

3.1.2 Behavior of Newly Emerged Young Ones

The young ones of most of the borers just after hatching enter into 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 into 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 direct application 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.

3.1.3 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 translaminar 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 borer management tactic.

3.1.4 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 gutter or 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.

3.2 Insect Ecology

The study of insect ecology provides the conceptual and theoretical framework which offers the practical ground for the application of pest management discipline. Recent advances in understanding the complex effects of insects and their interactions with other organisms on ecosystem services have influenced evaluation of the need for insect management (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 pest-entomophagous insect interactions which help to frame out the pest management strategy for any insect pest. In vegetable system, combining minimum tillage with cover crops and cover crop mulch creates enough biological diversity to pests. Such integrated practices resulted in conservation of field and increased beneficial insect populations 14 times higher than in the conventional fields. Leaving some undisturbed areas on a farm can help maintain the balance between beneficial and pest organisms. Many predators and parasites that attack crop pests thrive in the less-disturbed areas provided by hedgerows, weedy borders, woodlots and riparian buffers on the farm; in grassed alleyways in orchards and grassed waterways in field crops; and even in the small areas left between crop rows by zone tillage. Small sites allow natural enemies to persist and migrate into crop fields to keep pest populations in check. Maintenance of diversity in agroecosystem based on ecological studies of insect life and then diversity maintained in the crops grown can reduce pest problems. Maintenance of dissimilar types of crops growing at various stages and under diverse management practices will results in an encounter of pests with a broader range of stresses, they will face difficulties in locating their hosts in both space and time and their resistance to control measures also will be hampered (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. The dandelion flowers serve as source of food for nectar- and pollen-seeking insects before mowing them down. Insect ecological studies also laid the foundation of insect chemical ecology that yielded the discovery of so many semiochemials and their potential implementation in pest management program of so many insect pests (Pattison 2005). For example, discovery of pheromones (methyl euginol for fruit flies, gossyplure for pink bollworm etc.), allomones, kairomones and synomones are based on insect chemical ecology studies (Dhaliwal and Arora 2003; Dhaliwal et al. 2006; Saha and Dhaliwal 2012).

3.3 Information of Control Methods

The various aspects of the knowledge of technology help to select and use an appropriate pest management tool (insecticides, equipment). The knowledge of biological aspects of pest life highlights the appropriate place (where), timing (when) and procedure/method (how) for efficient application of any technology as well as for economically effective management of any pest (Buurma 2008; Pedigo and Rice 2009). Various aspects of any technology which lead towards its proper and effective application (Pedigo and Rice 2009) are given below:

- Nature and type of technology
- Mode of its application (aerial, foliar, chemigation, baits, traps etc.)
- Bio/shelf life of the technology
- Equipment required for its application
- Factors affecting the performance of technology
- Compatibility with other management tactics
- Target specific or broad spectrum
- Mode of action

3.4 Economic Decision Levels

The decision staircase of pest management program shows that successful and sustainable pest management depend on certain pillars 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 (Dhaliwal and Arora 2003; Dhaliwal et al. 2006; 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. An ignorance of these economic decision levels leads to ridiculous economic gaffes spending more cost on pest management and crop protection. 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 (Knipling 1979; Inayatullah 1995; 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 problems like ecological backlash (resistance, resurgence and replacement), pesticide residues and negative impacts on 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 insecticides.

3.5 Climate Change Management

Climate is changing due to global-warming associated with anthropogenic activities (Pachauri and Reisinger 2007). A comprehensive and long-term monitoring data and imperial-approach for feeding in modeling system is required to determine the impacts of climate change on distribution, outbreak, and dynamics of pests (Shaw and Osborne 2011). Gradual or abrupt increase in seasonal temperature, rise in the level of CO_2 and higher precipitation intensity are the major climate change manipulating factors (Pachauri and Reisinger 2007) which affect biology, development, physiology, epizootiology, phenology, distribution, invasion, population dynamics, (Willmer et al. 2000; Lamichhane et al. 2015), life history patterns, evolutionary adaptation (Bradshaw and Holzapfel 2011), distribution range (to suitable altitudes) (Parmesan 2006), and traveling speed (increases) (Aluja et al. 2011) of indigenous and invasive insects pest species (Fig. 1). Global changes also modify the host-pest-natural enemies' synchronization and interactions (both bi- or tri-trophic interactions), Synchronization in mutualistic interactions (pollination and seed dispersion) among species intensify losses potentials of pests (VanAsch and Visser 2007; Lamichhane et al. 2015), enhance adaptability of pest to changing climate (Trumble and Butler 2009), alter pest management protocols and strategies (low pesticide-residue IPM) and accelerate pest resistance buildup against control measure in practice (Lamichhane et al. 2015). A mild elevation in winter temperature due to climate change enhances the survival and colonization of previously low-temperature tolerant insect species which change their mode of reproduction from sexual to new asexual generation (Lamichhane et al. 2015). It has been reported that an increase of 2°C in temperature might result in 1–5 additional biological cycles per season in insects depending on insect species (Yamamura and Kiritani 1998).

Atmosphere enriched with CO_2 and O_3 influences plant quality, host plant selection and herbivory behavior of insects (Peltonem et al. 2006). Elevated ozone level in atmosphere indirectly influences insects by regulating insects associated bottom-up and top-down factors (Hillstrom and Lindroth 2008). Elevation in the level of CO_2 and O_3 will entirely change the insect community structure (abundance and diversity), population dynamics of hosts and biological control system due to substantial change in abiotic, bottom-up (resource concentrations) and top-down factors (predation, parasitism, pathogens etc.) (Dermody et al. 2008; Hillstrom and Lindroth 2008). Changes in rainfall, hurricanes and flooding can affect food-web dynamics, herbivory patterns, and insect-plant interactions due to alteration in the biochemical based plant-defenses (Koptur et al. 2002; Angulo-Sandoval et al. 2004). Climate change can also affect the production of plant volatile organic compounds (VOCs) which will influence the positive (e.g., pollination and seed dispersal) to

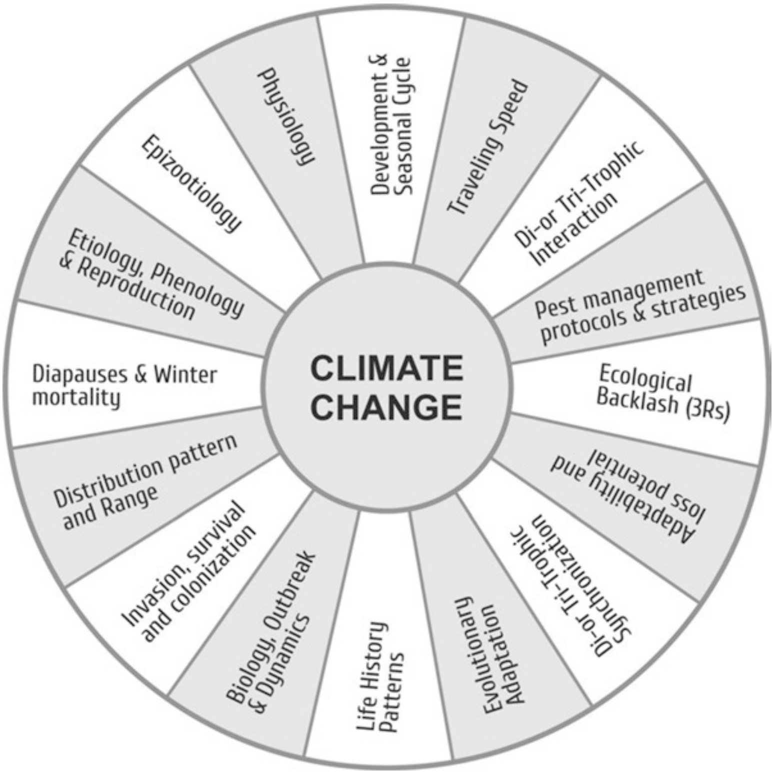

Fig. 1 Diagrammatic illustration of climate change impact on insect pest associated parameters including tri-trophic interaction, pest management practices, biotic potential, evolution and adaptations

negative (e.g., defenses against herbivory) insect-plant interactions (Penuelas and Staudt 2010).

3.5.1 Implications of Climate Change and Insect Pest Management

Agriculture and climate resilient sustainable pest management is crucial for sustainability of any pest management program. This imperativeness is attributed to the fact that climate change has been declared as one of the imperative factors which not only directly regulate agricultural productivity but also indirectly influence it by affecting regional and marginal distribution of indigenous and invasive pest species. Climate change also has significant effects on the biodiversity of pests, pollinators, crops and decomposers etc. It is, therefore, indispensable to execute modeling for biodiversity and climate change not only to devise climate resilient IPM but also to ensure sustainability of crop production and protection system (Fig. 2). Climate change has made the previously detrimental environmental conditions highly

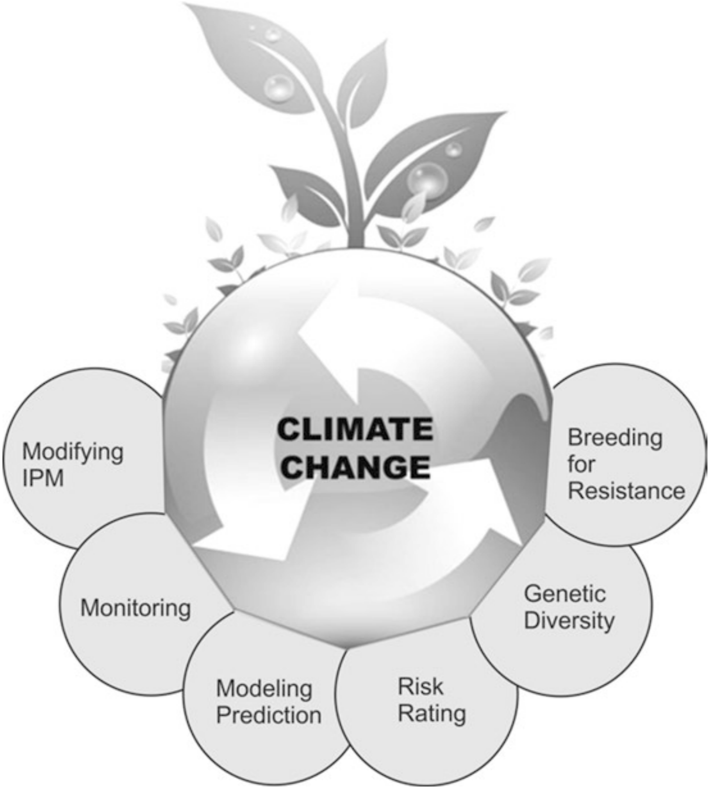

Fig. 2 Strategies for promising program of crop-health and sustainable ecosystem management against insect pests under changing climate conditions

favourable and conducive for less adapted indigenous as well as for exotic/invasive pest species. The least adapted pest species have become successful survivors under conducive climate changes than highly adapted species (Chakraborty 2013; Lamichhane et al. 2015). Extreme and excessive climate changes like severe and prolong dry, wet and warm condition may hamper crop productivity and effectiveness of the protection methods and technologies (Chakraborty and Newton 2011). Climate change may also cause severe increase in crop losses by pests and threaten food security (Lamichhane et al. 2015). Various models like CLIMEX have been utilized to predict the insects' responses to climate changes (Desprez-Loustau et al. 2007). However, insufficient knowledge on the interactions between climate change and disturbances (magnitude, severity or frequency insects' ecosystem disturbances) and inadequate information on climate-change induced modifications in insect-biology, host-resistance and phenology/physiology of host–insect interactions are major barriers in the modification of IPM strategies/programs. Following strategies can be exploited to address the issue of crop-health and sustainable-ecosystem management against insects under climate change.

- Modifying the conventional IPM to degree-day-model based IPM (Stacey and Fellowes 2002)
- Ensuring long-term efficient management of crops by coordination of monitoring data on spatial occurrence patterns of insects, ranges of host crops, growth, health and mortality of host-plants and efficiency of management tactics (Sturrock et al. 2011)
- Forecasting the prospective array of changes across a landscape and insects-attack outcomes using a diversity of modeling tools like climate models coupled with environmental envelopes, phenomenally diverse model and insects/climate-envelopes/host-reactions model (Hamann and Wang 2006; Sturrock et al. 2011)
- Application of crop-health strategies before the outbreak (epidemics) of insects using risk/hazard-rating system
- Increasing species and genetic diversity of crops to establish healthy plantation resilient to climate change (O'Neill 2008)
- Crop breeding for resistance and tolerance to pests and resilience to climate changes (Woods et al. 2010).

4 Stakeholders in Sustainable Pest Management

Stakeholders are individuals and groups of individuals who have a vested/staked interest in a particular issue, cause or enterprise (Dent 2000; Yang et al. 2009). Their expectations are built on experiences, assumptions and beliefs and will reflect specific organizational structures (Collins 1994). Within pest management, there are numerous stakeholders (Bryan et al. 2010), who can include, for instance, shareholders, managers, employees, suppliers, customers and communities who are all linked to different degrees to a commercial company that produces a chemical insecticide. In followings, there is an abridge description of the stakeholders categories with respective importance and roles.

4.1 Public Sector Agents and Agencies

The stakeholders in government need to establish policies that will work for the benefit of all other stakeholders (farmer, private sector, middle man etc.,) (Dent 2000; Freeman 2010). As stakeholders in pest management are so diverse in their interests and needs, henceforth governments perform balancing acts (Dent 2000). Public sector is responsible for funding public research interests in their institutes and universities; they are also responsible for ensuring that commercial companies generate new products which need to be manufactured, employing people, generating wealth and paying taxes (Altbach 2009; Parker 2009). Government policies including tax incentives made the production and use of pesticides attractive to business and farmers (Hall and Matos 2010). Pesticide development, production and use became institutionalized and in the same fashion, farmers became increasingly dependent (Zalom 1993; Alford 2000; Lamine 2011). However, with increasingly obvious environmental concerns raised about pesticides, there is also increased awareness of the public for these issues; thus, they became politically more important (Pimentel 2007; Damalas and Eleftherohorinos 2011). Henceforward, a balance of policy, which allowed environmental issues to be addressed but that, did not influence too heavily on the agribusiness, is required.

4.2 Research and Academia

The development of an IPM program, detailed knowledge of agro ecosystem and its components and how they interact in pest management is the job of scientists (Dent 2000; Feder and Savastano 2006). It has been argued that IPM is the creation of scientists, and these are scientists who have largely controlled its evolution, notwithstanding subject to pressures (Morse and Buhler 1997). The development of transgenic crop plants is one such example currently receiving a great deal of interest and, of course, funding (Marris 2008). The changes in seasonal abundance of a pest are easily described but much less easily explained. The understanding that is central to the philosophy of IPM necessitates an in-depth enquiry by scientists into the complexities and subtleties of insect biology and ecology (Dent 2000; Walter 2005). Despite the obvious role for interdisciplinary research in integrating control measures at a research level, the statement made by Pimentel in 1982 and 1985, still remains largely true today that: ‘most remain *ad hoc* efforts by individual pest control specialists, each developing so called integrated pest management programs independently of one another’ (Pimentel 1982; Dent 2000).

4.3 Industry

Commercial enterprises generate income through the provision of services, products or a combination of the two (Sievers and Vandenberg 2007). Within agribusiness, there is a greater emphasis on manufacturing and sale of products rather than the service side of the industry. Growers expect to budget for tangible items such as machinery, pesticides and fertilizer but the concept of purchasing, for example, is less acceptable (Zalom 1993). Whereas chemical pesticides were the predominate type of control product in the 1960s, since that time there has been a proliferation of different types of pest management products (de Faria and Wraight 2007). Proclamation made by Dent (2000) should be written with distinguished marks depicting that commercial companies are not in the business of alleviating the world’s pest problems, but rather, providing solutions that will generate a viable income and maintain the long-term prospects of the individual companies. The pest control business is worth billions of dollars worldwide each year, its presence influences the whole philosophy of pest management, continually driving for 'its' products (Dent 2000; Pimentel 2007). The commercial company stakeholders are major players in pest management affecting agricultural policy, R&D and also farmers' expectations and needs. The wealth and taxes, the employment and the assurance they generate, provide a powerful incentive for their continued role in the future.

4.4 Growers and Farmers

Farmers have often been viewed as passive recipients of pest management technologies (Pannell et al. 2006), however, this view is changing and farmers tend now to be seen as an integral part of the pest management stakeholder network, with a role in defining pest control needs, evaluating their effectiveness and influencing their wider adoption (Dent 2000). Farmers, more than any other group are sensitive to customer needs and the more competitive and intensive farming becomes the more consumers dependent leading to dictate the pest control practices adopted by farmers (Pimentel 2007). Farmers' objectives may vary. They may, for example, be interested in the maximization of profit or alternatively the minimization of risk (Zadoks 1987). Nevertheless, on both respect, their role remains essential in sustainable pest declines.

4.5 Final Product Users or Consumers

Consumers in developed countries have increasingly high expectations concerning food quality (Grunert 2005). In addition; there is increasing concern about pesticide residues on food (Boobis et al. 2008). It will be the need to maintain consumer confidence in the food industry that will continue to drive other stakeholders to invest in 'safe' technologies (Brunsø et al. 2002). This approach is being mirrored in developing countries that demands high quality standards (Napolitano et al. 2010). The concerns first expressed in *Silent Spring* have been maintained in the public arena by vociferous groups committed to environmentalism (Dent 2000). These groups, which initially campaigned successfully to maintain a high profile on the problems with pesticide use, are now equally vigilant and vocal concerning the potential hazards posed by genetically manipulated crop plants. Public concern may yet significantly influence the widespread use of these and other novel control pest measures (Alford 2000; Pimentel 2007).

5 Sustainable Legislature, Governance and Other Agricultural Regulations

Legislatures are very significant entities in controlling and regulating anything working in state area (Hopper 2016). In pest management, governing bodies and agricultural ordinances are appearing to be employed at national and international fronts to monitor pests, pest-mitigating products, food commodity; and henceforth; monitoring of invasive or out-placed pests (WHO 2015). These laws or codes have varying forms and formats (Peters and Law 2017). One of the fundamental forms, at country scale, is the establishment of quarantine ordinances and departments (Topinka 2009). Simultaneously, WTO inspections and agendas are at international arenas (Black 2017). Restrictions implied on the use of pyrethroids, on cotton in Columbia and in European areas, against *Helicoverpa virescens*, due to insecticidal resistance, is a prominent example at that time (Dent 2000). Ministry of National Food Security and Research is the propositional element under Government of Pakistan, working to frame Agricultural Pesticide Ordinances and Acts time-to-time (Ahmad and Farooq 2010).

5.1 Pesticide Ordinances and Orders

Regulations of pesticides and their products i.e., of biological or synthetic origins, are mainly done by government and its related institutes (DPP 2014a). They are relating not only to commercial pesticides but also to phytohormones (Alberto et al. 2016; Javed 2016) in plant protection. EPA and FDA with respective titles of ‘Environmental Protection Agency’ and ‘Food and Drug Administration’, are the basic governing bodies in US addressing these issues (Miller 2015). In Pakistan, Plant Protection Institutes-PPIs and PWQCPs ‘Pest Warning and Quality Control of Pesticides’ are playing those pivotal roles (DPP 2014a). At international sites, the Organization of Economic Co-operation and Development (OECD; an official governing body with different nations), United Nations Food and Agriculture Organisation (FAO) and WHO-the World Health Organisation, are the main working groups (Haya et al. 2015; WHO 2017).

FAO Article 6.11 in an ‘International code of conduct on the distribution and use of Pesticides’ has signify and intensify the considerations of legislations in words as: ‘governments should take action to introduce the necessary legislation for regulation, including registration of pesticides and make provisions for its effective enforcement, including the establishment of appropriate educational, advisory, extension and health care services’ (Dent 2000). Agricultural Pesticide Ordinance 1971 of Pakistan is in compliance with FAO, encloses directives for the importation, manufacture, preparations, trade, delivery and use of pesticides in Pakistan (DPP 2014a).

5.2 GM Crops Regulations

Since the introduction of biotechnology and other genetic tools in living world, scientists and others research institutes have to face huge controversies on the aspects of their GM crops regular incorporations in human globe (Qiu 2014). The removal of direct gene inductions, and making crops capable of self-defense by mediated inductive interference resistance, can also yield the equivalent crop protection and productions results (Javed 2016) without GM debates. Here, the aspects of supervisory measures mainly focusing on environmental safety, implications of gene shifting from GM to wild and also pollen contaminations of non-GM from GM, is prevailing (Qiu 2014).

However, an acceptance to GM crop can be granted, in US and EU, if GM crop satisfies and appears at par with the criteria for nearest conventional crop/product, i.e., in both botanical attributes and chemical constituency, depicting safety ranks for human and ecology (OECD 1993; FAO/WHO 1996). Animal and Plant Health Inspection Service (APHIS) are taking directives in US; and in Europe, the European Union implemented Directive 90/220/EEC in 1990, contracts with the proclamation and commerce of GMOs (Hygnstrom et al. 2014).

5.3 Quarantine Conducts and Orders

With the enhancements in global links and increasing trades across continents, have intensified the threat of pest transfer and introduction of potential pests in other countries (Dowell and Gill 1989; DPP 2014b) as by nature pests can have a limited expansion power by flight etc. Nevertheless fast trades and transports have facilitated them to move beyond the hemisphere (Hurley et al. 2016). Such activities preventing the introduction of any across border pests and are denoted under 'quarantine' with support of ministry of agriculture on legislative grounds (Mittinty et al. 2015). The things with considerations are plants, crop germ plasms, plant constituents, agronomic consignments, soil, vessels, stuffing, budding media, or any article that theoretically provide anchorage to exotic pests (DPP 2014b).

Government of Pakistan has formulated such conducts under the Department of Plant Protection with title 'Plant Quarantine Act 1976', the standing body is Ministry of Food, Agriculture and Co-Operatives (DPP 2014a, b). International Plant Protection Convention or IPPC has already loaded varying instructions and rules to prohibit any such cases (Hallman 2017). Any violation or mismanagement of such rules/orders lead to havoc as indicated from the plant products importation from USA in the form of American native *Helicoverpa armigera* (Hübner) or commonly statured American bollworm, with the present status of destructive key-pests in Pakistan and other regional countries (Kriticos et al. 2015). Most important quarantine pests in Pakistan, 'Plant Quarantine Act 1976' representing, are Black wart (*Synchytrium endobioticum* Schilbersky), Golden Nematode (*Globodera rosto-*

chiensis Wollenweber), Colorado potato beetle (*Leptinotarsa decemlineata* Say) and South American leaf blight (*Dothidella ulei* Hennings) (DPP 2014b).

5.4 Crop Production and Protection Legislations

Most of the crops are being infested by the pests when they are sown without paying any considerations to the prevailing pests' occurrence time, and thus, crops become susceptible to such pests (Sarwar 2012; Javed 2016). Any alternations in crop sowing time, cultural practices (Javed 2016) and changing cropping schemes can produce healthy crops with profitable results (Medvedev et al. 2015). But making and maintain the crop production rules are the sole responsibility of government to avoid any such pest threats (Lazpoulos Friedman and Van Camp 2016). Approval of warranted crop varieties, improved pesticides, plant defense mediators are need to be addressed for pest control. Sowing of rice nursery with planting time manipulation in Pakistan, to avoid yellow stem borer (*Scirpophaga incertulas* Walker) disposing off the double seeds of cotton to restrict pink bollworm and timely burning of crop residues and stubbles to prohibit litter dwelling insect pests, are few pest managing legislative examples (Attique et al. 2001). Similarly, on further perspectives, changing the planting geometries and varietal nature can also be helpful for such aspects (Sarwar 2012).

5.5 Biological Diversity Conservations

The case of sustainable pest control should not only assimilate the measures to mitigate or reduce the pest population/pesticides, rather, for instance, with reference to biocontrol agents (de Melo et al. 2018), must involves and encompass the measures to conserve biological diversifications of fascinating world (Ong et al. 2016). Biocontrol agents are the natural non-paid labor and farmer assistant with no proper attention of crop protection community (de Melo et al. 2018). There should be such legislative endeavors to conserve those (Sutherland et al. 2017). The supreme imperative international episode was 'United Nations Conference on Environment and Development (UNCED)', Rio de Janeiro in 1992 leading to scientific documentation title 'the Convention on Biological Diversity, that was later ratified in 1995 by 142 countries around the world with 'Agenda 21', embraces a subdivision/chapter 14 on 'Promoting Sustainable Agriculture and Rural Development'. This compacts utterly with the glitches of pesticide over employment, thus flashing, Integrated Pest Management along with, further, to launch operative and collaborative linkages among farmers, academics and extension personnel lead facilities to uphold IPM task (Dent 2000; Sherman et al. 2017).

6 Sustainable Management Approaches for Insect Pests

Since the first introduction of integrated control term, integrated pest management strategies has increasingly received attention as a practical solution to pests without ecological backlashes (Stern et al. 1959). Sustainable pest management techniques in crop protection emphasizing systematic approaches focusing on preventive and curative methods drawn from a wide array of connotations (Fig. 3). It mostly encompasses physical, agronomic, mechanical and biological principles resorting to selective reduced risk pesticide when addressing situations cannot be effectively managed with other control tactics (Gadanakis et al. 2015). Sustainable management approaches aims to mitigate the input of pesticides and lessen detrimental effects of chemicals on non-target organisms and the environment. Today sustainable management approaches has become a fundamental strategy of sustainable agricultural arthropod pest management in developed and developing countries (Peshin et al. 2009). Moreover, durability of sustainable control approaches relies on the diverse array of solution, rather than repeated use of a single management approach (Barzman et al. 2014).

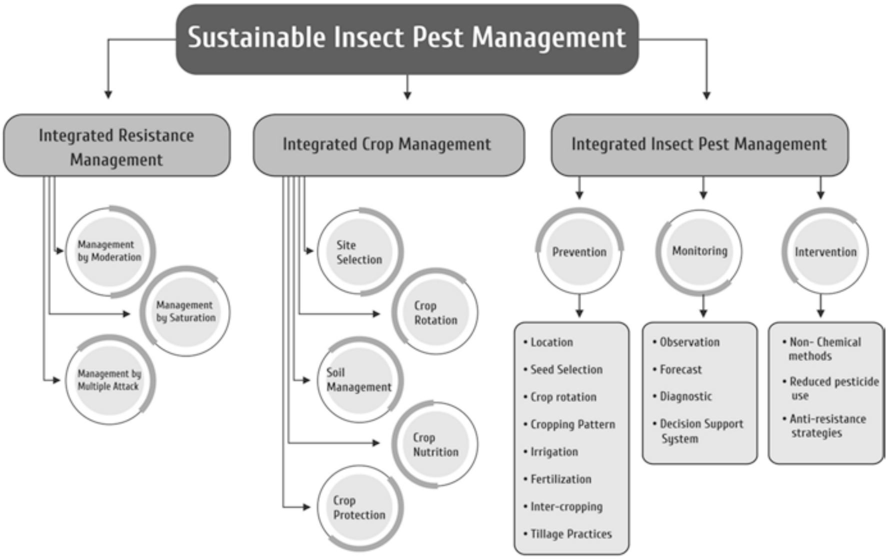

Fig. 3 Sustainable insect pest management techniques (IIPM, IIRM, ICM) in crop protection emphasizing systematic approaches focusing on preventive and curative methods drawn from a wide array of connotations

6.1 *Integrated Insecticide Resistance Management (IIRM)*

Insecticides, being the necessary entities are neither accepted nor denied in sustainable agricultural productive mechanics (Rother 2018). Additively, indiscrimination or undesirability in employments are making theme to be strongly deterred among eco-activists (Joshua 2017; Rowell 2017). But the most prevalent problem of present pest management is accompanied to be linked with the pervasiveness of insecticides so there is some sorted 'tilt at the wind mill' ignoring judicious strategies. No doubt, excessiveness in utilization of pesticides, henceforth creating the insecticidal resistance predicaments (Pedigo and Rice 2014; Rowell 2017), is the dire focal considerations to discourage insecticides but the blunders on behalf of insecticides applicator/farmers need to addressed too (Rother 2018; Sudo et al. 2018). The forum of discussion not only can assist to solve the prevailing resistance issues but pave a glaring way toward Integrated Insecticide Resistance Management (Fig. 4). IRAC (2018) has asserted a well accomplished integrated approach in this regard. This being apparently a single topic, is overwhelmed and encompassed broader ranges of resistance responsible representatives (Fig. 4). These may be either of operational (prolonged exposure/use of single active ingredient insecticide, high lethality/causality pressures, immediate knockdowns, no/zero percent refugia, agri-advisories insufficiencies) or biological ones (monophagy of pest, multi-volatility and high mobility) (Pedigo and Rice 2014; Elahi et al. 2018; Arain et al. 2018; Sudo et al. 2018).

Nowadays, the core theme of focus for management and mitigation of pest/insecticides resistance is incorporating the integrative measures at multiple dimensional strategies (Fig. 4) i.e., inculcation of moderation, saturation and multiple attacks as depicted by Pedigo and Rice (2014).

6.1.1 Mitigation by Moderation

That is basically preventing any paradigm gene shift from vulnerable to resistance genes acquisitions by the insects hence making population more insecticide hazard free (Pedigo and Rice 2014). On the other, conservation and increments of bio-control agents along with natural eco-arena is also achieved under 'moderation' (Arain et al. 2018; Joshua 2017; Rowell 2017). On a broader approach, it uses less dosage, leaving some vulnerable pest population, less persistent agro-chemicals and localized application as the dire flashing points, i.e., prohibition of all extremes (Pedigo and Rice 2014; Rother 2018).

Fig. 4 Schematics of integrated insect resistance management occupying sub/genes level to main/field levels depicting integrative approaches in all aspects

6.1.2 Mitigation by Saturation

Saturation is basically involving intermingling the pest built-in defenses in such a manner that it cannot remain further capable of coping the insecticide exertive pressures (Sudo et al. 2018). This either be achieved by imposing the resistance genes to be in susceptible categories especially by making *R* gene as recessive or may be by repressions of detoxifying in insects, e.g., UDP-glycosyltransferases/metabolized systematizations in Drosophila (Arain et al. 2018) and by the synergism of piperonyl butoxide in spray mixes (Pedigo and Rice 2014).

Mitigation by multiple-attacks: Multiple-invasions in any cases render the target organism to be in confusion, henceforth decline its ability or total collapse to counter-act. The same scheme can be applied on field levels, but on lower intensive scales for resistance integrated management (Pedigo and Rice 2014; Sudo et al. 2018). These may be applying the insecticides in permitted mixtures; compatible insecticide sprays in assortment patterns, and of course, insecticides replacements/alternations with novel modalities (Arain et al. 2018; Sudo et al. 2018).

The other commonly prevailing strategies in normally nominated 'IIRM' escorted by the fundamental theme point of coordinated techniques with furthermore reconciliation of various administration strategies (Fig. 4), by IRAC (2018) and relevant researches, can be elaborated as follows.

6.1.2.1 Economic Considerations on Pest Levels

Option of insecticides utilization as final assertion is only if pests square-up adequately to cause financial calamities/monetary loss (Pedigo and Rice 2014). Otherwise, on the far side retrospect and prospect, the estimation of insecticides abuses not only far reaching but may be aggravated. Aggravation may be apparent as deformed fruits, pre-mature crop evacuations or sever defoliation with burnt phyto-textures along with pest resurgences (Arain et al. 2018; Sudo et al. 2018).

6.1.2.2 Integrated Insecticide Administration Strategies

The fusion of the most critical possible scope of different insecticidal administration techniques (Pedigo and Rice 2014; Rother 2018) with incorporation of the working efficiencies of chemicals/multiple toxins, botanicals and bio-pesticides with simultaneous tendency of parasitoids/entomo-pathogens has always yielded commendable outcomes (IRAC 2018; Sudo et al. 2018). But importantly, the inclination toward eco-friendly tactics must not sacrifice the pest decrements, henceforth must be assimilated with other cultural crop sanitation programs. It is a key crucially to maintain the action of sphere with pesticides timing, pest dynamicity and over-dose despondencies (Pedigo and Rice 2014; IRAC 2018).

Integration of altered insecticide class sprays with cropping/pest cycles: One of the key components of powerful resistance-mitigated program and so forth pest protection framework, is the utilization of pivoted grouping of altered classes synthetic cum novel pesticides (Arain et al. 2018; Rother 2018). Additionally perpetual spray cycles, all through the cropping yield and/or pest cycles, should be rendered active by 1 year or so, rather than focusing on single insecticide/seasonal pest optimized management (Sudo et al. 2018). It is of utmost considerations that pest can naturally integrate them with cropping patterns/cycles but the integration of spray programs must be executed on personal willpower for encouraging pest/resistance predicaments hold under proper agri-advisories and ecological safties (Rowell 2017; Elahi et al. 2018).

6.2 Integrated Crop Management

The development of agriculture production system has advanced into a variety of socio-economic and socio-ecological conditions especially in the developing countries. The wise use of natural resources is the key for the long term sustainable production levels in different cropping systems (Meerman et al. 2008). In the recent years it has become obvious that the pest management requires selective use of control methods for the sustainable agriculture. In the days to come farming system is shifting towards a blend of traditional and modern insect pest management approaches. Integrated pest management is a part of integrated crop management

(ICM) that is not only a form of crop production but a dynamic system that adapts the wise use of latest technologies for agriculture productivity. Integrated crop management is the key in response to farmer's concern and related economic liabilities (Leake 2000). Integrated crop management is a holistic approach that reflects the prevailing conditions on the farm with a consideration of sound economic and environmental factors for the sustainable agriculture. There are several components that involve in the integrated crop management e.g. site selection, crop rotation, soil management, crop nutrition and the crop protection (Kumar and Shivay 2008).

6.2.1 Site Selection

Optimal growing condition is the key component of integrated crop management that provides appropriate plant growth features from seedling onwards. Adjacent crops and environmental conditions should be considered while selecting the location of planting new crop. Moreover considerations should be given to overwintering pests that can move from neighbouring ignored habitats (Pedigo and Rice 2009).

6.2.2 Crop Rotation

Growing different crops in a rotation pattern helps to reduce pest buildup both above and below ground regimens especially when the pest has narrow host range, egg laying before new crop plantation and the damaging stage not very mobile. Rotations have been successful for arthropods that target roots and cannot move out the area to obtain their food requisites. Crop rotations with longer period of time and with the adding of more new crops in the area can better manage the soil pests of several crops (Pedigo and Rice 2009). Furthermore diverse rotation can also reduce the impact of weeds and involves breaking the life cycle of antagonists to keep them below threshold levels which would ultimately require pesticide application (Leake 2000).

6.2.3 Soil Management

Soil is the essential natural resource provides stability, structure and fertility to the crops; that needs to be managed properly and is vital component of any ICM plan. Sometimes erosion caused by various factors (wind, water) triggered unhealthy effects on some soil types and it is quite important to minimize those factors. Measures might be taken by planting permanent grasses however care should be taken while establishing rotation pattern. Moreover alternate ploughing and non-inversion techniques should have been adapted in the rotation while establishing integrated crop management.

6.2.4 Crop Nutrition

Diverse soil types exhibit different amounts of nutrients required for healthy plants. Plant nutrition management is also another key component of ICM that provides necessary nutrients at right time for proper growth of plants. Moreover, planned nutrients inputs are the key to enhance the crop production and maintain the economically and environmentally sound soil fertility for the longer period of time. However care should be taken while fertilizers application that might create unhealthy effects on beneficial fauna of the soil.

6.2.5 Crop Protection

The invasion of pests and other diseases is inevitable in any farming systems. Much can be done under the umbrella of ICM programs for the effective control of damaging pests without disturbing other practices in the holistic management of the farm. One of the essential aspects is the adaptation of prevention strategies as a first line of defense to keep the pests below economic threshold levels. Although severity of pest and disease may varies depending on the agro-ecology, genotype susceptibility, crop growth stage and locality etc. Adaptation of modern crop protection strategies using a combination of cultural, physical biological and chemical methods within the requirements of ICM can play a pivotal role in sustainable agriculture.

6.3 Integrated Insect Pest Management

Man has to compete with the insect pests from the pre-historic days that cause severe economic losses to agricultural crops worldwide. Insect pests are considered a major constraint to achieve global food security and poverty alleviation especially in the developing countries due to lack of management technology. To overcome this problem the use of pesticides for pest management presents additional negative impacts on ecosystem; and it is now clear that alternative holistic control methods needs to be applied for sustainable agriculture. Integrated insect pest management is an important substitute method of rationalizing synthetic pesticides use to avoid or delay pest resurgence and to protect the natural enemies in the agriculture ecosystem (Alastair 2003). Integrated pest management has been used in varied inferences and the term was first used as “integrated control” by Bartlett in 1956 and was further elaborated in 1959 by Stern and his co-workers.

Integrated pest management system is the socioeconomic in the perspective of farming system, the associated environment and the population dynamics of pest species, utilizes all suitable possible techniques to keep pest below economic thresholds (Pretty et al. 2011; Pretty and Bharucha 2014).

Integrated pest management highlights pest problems followed by simultaneous integration of different tactics, the regular monitoring of insect pests and natural enemies and a thresholds assessment for decisions. After the proper identification of pest damage and the responsible pests there are different tactics i.e. cultural, physical, genetic, biological, chemical and regulatory methods to suppress the pests (Ehi-Eromosele et al. 2013). Integration or compatibility of these management practices is the key in integrated pest management programs for sustainable development. Dependency on a single pest management method may have undesirable effects on ecosystem. Moreover reliance on a single management practice might favor pests that can cause resurgence in future cropping system. So for that IPM takes the advantage of using all appropriate management methods in integration with judicial use of pesticides. Integrated pest management practices include; planning, regular monitoring and timely decision that play a key role for sustainable crop production. Some of the important IPM control methods are;

- **Cultural methods** – these are the practices that make the less favorable conditions for pests' establishment, their reproduction, dispersal and survival. Moreover by adjusting crop location, time of sowing or crop rotation and cultivation techniques also destroy their food, shelter, breeding habitats and exposing them to predators play a significant role to keep pest population below threshold levels.
- **Mechanical and physical methods** – using these methods pests can be controlled directly or make the conditions unsuitable for them. The insect pests can be kept away using barriers and traps or physically remove them from the target area. Moreover hot or cold treatments make the environment unsuitable for insect pest developments provide control at key times.
- **Genetic methods** – insect-resistant varieties developed by classical breeding or via genetic engineering suppress pest population or elevate plant tolerance level through insect movement interfering their feeding behavior or reproduction on or in the plant. The resistance can be generated by change in color, thickness of the cell walls or plant tissues, surface wax, trichomes (hairs) or spines etc.
- **Biological methods** – it's a self-perpetuating use of natural enemies including predators, parasites or microbial pathogens to suppress pests for an extended period of time than other methods of pest control. Biological control agents can help to suppress pest populations by competing with the same pest resources or by parasitism or predation of the target pest species.
- **Chemical methods** – chemical control is a cure-all for pest problems and is the best practical and cost effective technique to bring population below economic threshold levels. Regardless of the synthetic pesticides used, there are several considerations like mode of action, delivery, selectivity and resistance should be addressed before application.
- **Regulatory methods** – include all forms of legislation and regulations that might prevent, establish or the entry or spread of pests and restrict the movement from one area to another. Additionally, regulatory control gives growers and producers a short reprieve before invasion of the pest and provides a cushion time for better management.

7 Integration of BC with Insecticide Application

As an alternate for the sustainable pest management in the 21st century, the opportunities and demand for the effective biological control are greater than ever before (Bale et al. 2008). Although, the level of pest suppression using bio-control agents have never been exceeded from 50% (Hall and Ehler 1979; Hall et al. 1980) and the success rates may vary depending on environmental conditions. For the sustainable insect pest management, biological control is more effective when coupled with other integrated pest management (IPM) tactics. Among these strategies, making pesticides more compatible with bio-control agents is one of the key combinations keeping pest population below economic threshold level with least disturbance of ecosystem.

Although pesticides have variety of unpredictable negative impacts on closely related beneficial organisms; however pesticides still remains an integral component of sustainable pest management strategies (Guillebeau 2004). However pesticides can be used in a variety of modified manner (e.g. selective use of active ingredients and formulations, only when economic thresholds dictates, temporal and spatial separation of natural enemies and pesticides, use of lowest effective rates of pesticides) to protect the natural enemies in the ecosystem (Hull and Beers 1985; Poehling 1989; Ruberson et al. 1998). Moreover it is worth to know that natural enemies can recuperate quickly even when broad spectrum pesticides have been used, particularly if they are easily degradable, and recolonization of population in the refuge areas at margins. Differences regarding susceptibility among taxonomically close species have been documented in some studies and even within the same species strains. Adults of *Eretmocerus mundus* Mercet parasitoid were less susceptible to cypermethrin, amitraz and thiodicarb residues compared to *Encarsia formosa* or *E. pergandiella* Howard (Jones et al. 1995). Additionally there are several studies that showed predator/parasitoid tolerance against some insecticides even when there is no indication of resistance in the natural enemies (Guillebeau 2004) resulted unpredictable impact of broad spectrum pesticides on beneficial insects. For instance, *Chrysoperla rufilabris* (Bermeister) adults and larvae showed toxic susceptibility towards organophosphates and carbamates; while pyrethroids were non-toxic to this natural enemy (Mizzell and Schiffhauer 1990). On the contrary, organophosphates were non-toxic to some predatory beetle compared to pyrethroids. There are clear indications of varying impacts on natural enemies within a single group of pesticides. In another study, cypermethrin was recorded less toxic than permethrin to parasitoid; but in case of predators reverse effect was observed (Wright and Verkerk 1995). Furthermore, the sublethal effects of pesticides on natural enemies make more complications. For example, some Braconidae minute wasp females lay fewer viable eggs when exposed to sublethal doses of carbaryl (Grosch 1975). Similarly decreased fecundity has been recoded for some coccinellids after sublethal effects of organophosphates (Parker et al. 1976). Similarly formulations improve the selectivity of pesticides to protect the natural enemies. For example dust formulations that are more toxic to beneficial than powders or emulsifiable concentrates that can cause mortality of some parasitioids even in the absence of pesticides. Irrespective of the chemical used there are few considerations that should be addressed before applications.

- **Mode of action:** generally mode of action needs to be designed so that the pest can be targeted at weaker stage of their life cycle.
- **Delivery:** pesticides application should supremely be multi-disciplinary in order to minimize their impacts on ecosystem and must have target specific.
- **Selectivity:** while making a treatment decision careful selection of pesticide is quite necessary to spare natural enemies. However selectivity sometime differs from specificity that is the ability of a compound results higher mortality for the particular target pests (Fisher et al. 1999).
- **Resistance:** information regarding resistance has been observed in either the pest or natural enemy or the exposure of target pest to a particular pesticide before and the potential for the resistance buildup of in the target pest population against a particular chemical should have been carefully examined.

Making pesticides more compatible with biological control system; placement and careful timing of pesticide application can minimize the pesticide contact with natural enemies. Additionally selective treatment with non-persistent pesticides can limit overall negative effect on beneficial population of insects in the cropping ecosystem and these types of pesticides should also be considered in integrated pest management programs.

8 Use of Insect Behavior Modifiers

The natural phenomena regarding an organism's behavior in response to external or internal stimuli released by other organisms of the same or other species (or different phylogeny) play a key role in insect-plant interactions. Eco-physiological, biochemical and behavioral processes involve in insect plant interactions in which secondary metabolites play a significant role. For their development insects have adapted to these phytochemicals; using them as cues for host recognition or other biological activities. Change in structural diversity of plants with the passage of time has resulted in synthesize of substances like, phenolic compounds, non-protein aminoacids, terpenes, alkaloids and flavonoids that ultimately led to behavioral and biochemical adaptations in insects towards plants. Primarily most of the insects rely on olfactory receptors to contact with the external environment (Krieger and Breer 1999). Insect's attraction towards plants or other host organisms involves the recognition of specific semiochemicals (Fig. 5) or specific ratios of these compounds (Bruce et al. 2005). For the sustainable management of insect pests, there is an opportunity to develop interventions using semiochemicals that influence the behavior of noxious insect pests in agriculture, forestry, horticulture, stored food products and insect vectors of several diseases. Semiochemicals are signaling chemicals naturally produced by insects that transmit chemical messages. Semiochemicals provide environmentally safe, non-toxic and species specific alternative solutions for pest management in different cropping systems. Moreover, semiochemical's role as pest repellents and natural enemies attractant can be helpful keeping pest populations below economic threshold levels without harming agro-ecosystem. Semiochemicals can be classified into allelochmeicals which have interspecific interactions and pheromones with intraspecific interactions (Fig. 5). Furthermore allelochemicals divided into allomones signals in which emitting species benefits, kairomones when receptor species get benefit and synomones when both species have the advantage (Nordlund et al. 1981). Antimone are harmful for both emitter and the receiver, e.g. non-host chemicals arrest parasitic wasps (honeybees); while in case of apneumone chemical signals from nonliving sources like salt and there is no benefit damage to the emitter.

One of the most widespread and successful application of semiochemicals is the detection and monitoring of pest populations (Witzgall et al. 2010) to justify the pesticide use before exceeding the economic thresholds. Pest sampling/scouting is always a laborious and expensive especially on large scale areas. In this regards sex pheromones are key and have the potential to suppress or eradicate low density populations and are effective for tracking invasive species in the establishment phase (El-Sayed et al. 2006; Liebhold and Tobin 2008). Sex pheromones based threshold action was taken first time by monitoring pea moth *Cydia nigricana* in England from 1980–1985 (Wall et al. 1987). Similarly, a pheromone-based monitoring system was developed at Rothamsted, UK for the orange wheat blossom midge (OWBM), *Sitodiplosis mosellana*; a serious pest of wheat in Northern Hemisphere causing severe losses to crop yield (Bruce et al. 2007). In another studies pheromone based field monitoring for Agriotes spp. have been successfully conducted in Europe and North America (Vernon and Toth 2007; Toth et al. 2008; Sufyan et al. 2013). Apart from pest monitoring, pheromone-based mass trapping,

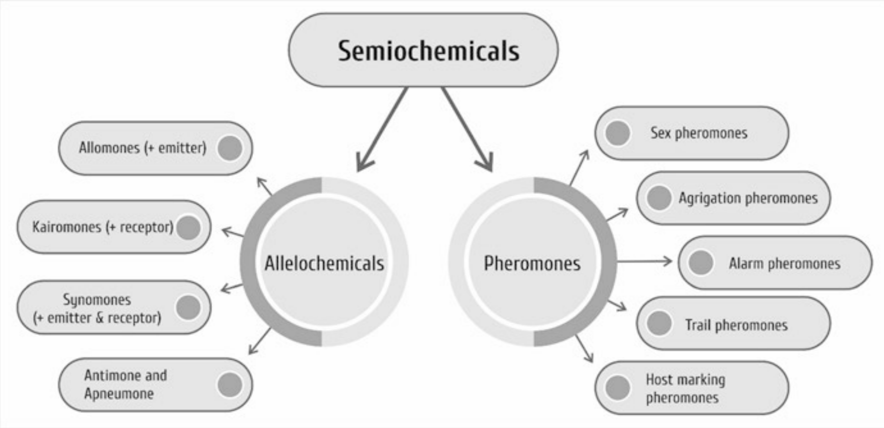

Fig. 5 Schematic diagram of different types of semiochemicals (allelochmeicals and pheromones) which can be exploited for the management of different insect pests in different crops

mating disruption and lure and kill techniques has been applied in the integrated pest management programs successfully for several decades. From the last four decades more than 200 studies have been conducted for mass trapping of pests from Lepidoptea, Homoptera, Diptera and Coleoptera (El-Sayed 2012; Alpizar et al. 2012). Some of the most successful mass trapping attempts of pest management against *Leucinodes orbonalis* Guenee (Cork et al. 2001, 2003, 2005), *Dendroctonus* spp. and *Ips duplicatus* Sahlberg (Silverstein et al. 1968; Schlyter et al. 2001) and *Ephestia kuehniella* Zeller (Trematerra and Gentile 2010) has been recoded with a significant reduction of pesticides consumption and resulted significant increase in crop yield. The blend of mass trapping with insecticides composites into "lure and kill" or attracticides (Jones 1998); the approach have been used in integrated pest management programs for the last several decades documented in numerous studies (El-Sayed et al. 2009). Similarly attract and kill technique has been successfully employed for the management of cotton boll weevil (*Anthonomus grandis*) in USA and South America on several thousand hectares (Ridgeway et al. 1990; Smith 1998), fruit flies *Bacterocera* spp. in USA (Cunningham et al. 1990; Hee and Tan 2004; Vargas et al. 2010; El-Sayed et al. 2009). Correspondingly pheromone mediated mating disruption is also an alternate sustainable pest management strategy by disrupting chemical communication among organism that reduce chances of organisms reproduction and ultimately reduce future pest population. The area under mating disruption has been significantly increased from the last 2–3 decades with 770,000 ha globally in 2010 (Ioriatti et al. 2011; Witzgall et al. 2010). Mating disruption is more effective on large areas because the large areas permeated with synthetic pheromones reduce the impact of gravid females to immigrate into treated areas. A wide range area under the infestation of gypsy moth (Lymantria dispar) in North America forests, codling moth (*Cydia pomonella*) in apple trees globally and the grape vine moth (*Lobesia botrana*) in the EU and Chile grapes fields has been managed by permeation of synthetic sex pheromones in the infested areas (Witzgall et al. 2010).

The prospects of semiochemicals considered to be an encouraging in the future biological pest management programs. Since pheromones are cheaper, easily available and species specific that facilitate integrated pest management more efficiently without harming beneficial insects in agriculture. However much remained to be known about plant defense system; that can be improved in future by breeders and become as widely used as pheromones in field situations; where pheromones have been essential part of pest management programs for the last four decades.

9 Conclusion

Crop pests, diseases and weeds are a serious threat to global food security, poverty alleviation and other agricultural products. The sustainable management of insect pests is quite challenging due to interference of some biotic and abiotic factors especially the climate change and global warming. The extent of losses due to insect pests is expected to increase in future due to changes in crop diversity, pest types and changing environmental conditions. Moreover, the changing environment also interferes with the normal functioning of various pest management strategies like host-plant resistance, biological control methods and chemical control.

Sustainable insect pest management strategies including integrated pest management and integrated crop management is much more than just a simple resource-conserving technology.

A successful adaptation of IPM plan against certain insect pests also accounts for the protection of beneficial insects, secondary pest outbreaks, pest resurgence and ecological backlashes. Moreover, the use of non-chemical control methods based on the philosophy of integration of indigenous natural enemies with other biological control techniques to partially replace the synthetic chemicals is worth considering. Although non-chemical control methods of insect pests can be utilized for longer period of time; however these measures may be insufficient to manage the outbreaks of migratory pests. Therefore, integration of non-chemical control methods with synthetic pesticides will be a promising option for sustainable insect pest management.

Moreover the use of therapeutic tools (biological, chemical, physical, mechanical and resistance management) are considered primary means of regulating pests rather than as occasional supplements to keep them below economic thresholds. Additionally the focus should be on the development of farming practices that are more compatible with ecological systems and cropping patterns that naturally limit an organism to attain pest status. Furthermore, there is need to understand and address pest management issues by keeping on board the other crop producing stakeholders for the sustainable insect pest management.

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