Indian Journal of Entomology 85(1): 277-291 (2023) DoI. No.: 10.55446/IJE.2022.807

RECENT ADVANCES AND CHALLENGES IN IMPLEMENTING IPM PROGRAMMES IN THE ENTOMOLOGICAL CONTEXT OF INDIAN AGRICULTURE

Ruchika Geedi and Gadi V P Reddy[1*]

USDA-ARS, Application Technology Research Unit, Horticultural Insects Research Lab, 1680 Madison Ave. Wooster, Ohio 44691, USA

[1]USDA-ARS, Southern Insect Management Research Unit, 141 Experiment Station Rd., Stoneville, Mississippi 38776, USA

*Email: Gadi.Reddy@usda.gov (corresponding author): ORCID ID 0000-0001-6377-0721

ABSTRACT

Integrated pest management (IPM) programmes are based on using multiple methods to maintain nuisance insects below tolerant levels in crop fields. Recent advances in IPM in developed countries have incorporated biological pesticides, microbial products, semiochemicals, and beneficial insects, but few of such programmes have been successfully implemented in developing countries, such as India. Semiochemicals play critical roles as signals in various interspecific and intraspecific interactions between insects and plants, and among interacting insects, plants, and microbes. In India IPM programmes have included mechanical, chemical, cultural, and biological management strategies. However, among these methods, biological management has its own limitations. Indian IPM scientists mostly work on individual crops, assessing damage severity by specific nuisance arthropods and the efficacy of particular management measure. However, very few government institutions or commercial companies are engaged in developing and commercializing either biological pesticides or semiochemicals. Government institutions mostly focus on research on pheromones of the pestiferous Lepidoptera and Coleoptera. Developing IPM programmes requires a clear understanding of crop-plant development, biology and population dynamics of the nuisance organisms, and the chemical and molecular interactions between the two. It also necessarily requires local knowledge of available, prevalent management tactics. Moreover, the IPM programmes have not been widely adopted in developing countries due to lack of proper knowledge and training farmers in efficient IPM practices, the need for more of human labour, and the complexity of IPM practices, all of which impede on the effective implementation of IPM programmes. In this article, we recapture the historical development of IPM efforts in India and ask whether this concept remains suitable to the present-day challenges in crop production. In this review, more specifically, those factors identified as obstacles to the more widespread adoption of IPM and ways of overcoming such barriers are discussed.

Key words: IPM programmes, present status, adoption, barriers, beneficial insects, biological pesticides, challenges, microbials, botanicals products, semiochemicals, severity, insect plant interactions

Agriculture is the world's largest industry, employing more than a billion people and generating 1.3 trillion-dollar worth of food annually. Crop production is vital in the economic development of any country. In India, ≥75% of people depend on agriculture for livelihood (Kataria and Kumar, 2012). Agriculture employs roughly half of India's workforce and contributes to 17% of India's GDP. India is characterized by an immense diversity in climate, topography, flora, fauna, land use, and socioeconomic conditions (Hinz et al., 2020). Numerous studies have found that biodiversity influences the primary productivity of ecosystems and other aspects of ecosystem functioning. It is also experimentally established that the productivity of many terrestrial ecosystems depends on the availability of limited resources such as soil nitrogen, water, CO_2, herbivory, diseases, and disturbances such as fire or drought (Tilman et al., 2012). India has experienced notable increases in agricultural productivity over the last decades (Hinz et al., 2020). A report by the Department of Agriculture, Cooperation and Farmers Welfare (DAV&FW) reported that the food-grain production in India would be 279.51 mt in 2017-2018. The per capita net availability of food grains increased over time. For example, the per capita net availability of edible *Oryza* sp. (Poaceae) was 58.0 kg/ year in 1951, which has increased to 69.3 kg/ year in 2017, but the area under the cultivation of *Oryza* sp. increased from 30.81 m ha to 43.95 m ha (Nelson et al., 2019).

Pestiferous arthropods damage 18-20% of the world's annual crop production, valued at US$ 470 billion (Sharma et al., 2017). However, losses because of pestiferous arthropods are often considerably higher in the Tropics that mostly include developing countries in Asia and Africa, where most of future increases in human population are expected to occur in the next 50 years. In India the highest crop losses are in *Gossypium* (50%), followed by *Sorghum* (30%) and different millets (30%), and *Oryza*, *Zea*, and various oilseeds (each 25%) (Dhaliwal et al., 2015). Farmers through the world actively use pesticides to suppress nuisance insects. Boedeker et al. (2020) reported that 4.1 MT of pesticides were used worldwide in 2017. However, in recent years, with the growing awareness among consumers regarding pesticides residues in crops and their impacts on non-target organisms and human health has caused farmers to reduce the use of pesticides. The use of alternative management practices as in IPM can enhance consumer acceptance and the sustainability of crop-management systems. The IPM programmes must be based on a thorough understanding of the ecology of the concerned organism and its associated natural enemies and their collective interactions with the crop. IPM programmes increasingly validate an understanding of host-plant resistance, smart use of natural enemies, and redesigned agronomic practices (Alwang et al., 2019). In this article, recent advances in IPM are discussed, and the challenges faced by India to implement the newer practices in IPM programmes are explained. Non-chemical IPM approaches are valuable because of the indiscriminate use of chemical pesticides has led to increased crop production costs concurrently with severe harm to the environment, natural enemies, and human health.

Here, the diverse forms of non-chemical approaches, e.g., use of microbial agents, parasitic and predatory arthropods, entomopathogens, antagonistic microbes, endophytic fungi, botanicals, and crop residues with pesticidal properties into three broad categories (Rao and Rao, 2010). First, augmentative biological control is considered, using predatory and parasitic arthropods. Second is the replacement of synthetic-chemical pesticides with either botanicals or microbes. Third, is the efficacy of semiochemicals in the management of nuisance insects.

A. Present status of IPM in India

Presently, the IPM programmes for managing problems caused by nuiscance arthropods emphasize the adoption of cultural, mechanical, biological, and chemical management (Fig. 1), which are collectively

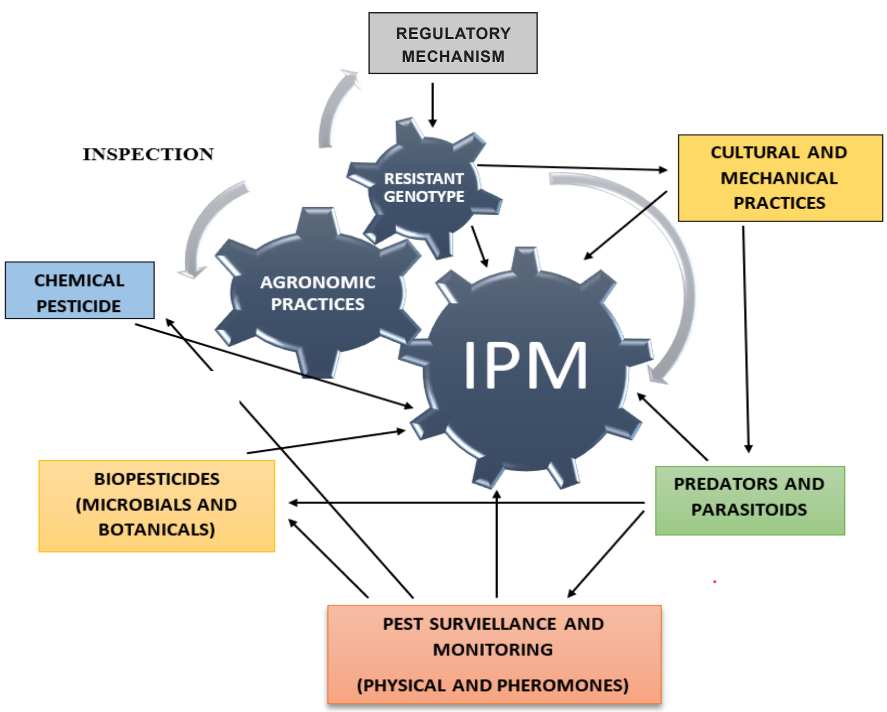

Fig. 1. Schematic diagram of IPM- Black arrows indicate different strategies (physical, mechanical, chemical, cultural and biological controls) associated with IPM modules. The grey arrows represent agronomic practices, resistant genotype, and regulatory mechanisms interconnected with IPM

employed to restrain populations of nuisance arthropods below the economic thresholds (ETLs) (for statistical details, see Bhagat et al., 2016). Most of the Indian farmers (73%) launch nuisance-arthropod-management measures at the time of the first appearance of the concerned arthropod, regardless of the density of the infesting arthropod, developmental stage of the crop, or the interaction patterns between the infesting arthropod and the crop plant (Bhagat et al., 2016). The cost of plant protection on various crops in India range from 7 to 40% of the total crop production cost in the year 2009. Indian farmers see pesticide use as the best means to protect crops from arthropod damage.The synthetic pesticides liberally available in the Indian market include organophosphates, organochlorines, carbamates, synthetic pyrethroids, and neonicotinoids. These are applied both individually and in combination. Although the conventionally used synthetic insecticides usually provide quick and adequate control in the short run, they are expensive (Singh et al., 2012) and pose health hazards, risks of developing resistance in the arthropods thus encouraging tsunamic resurgence of nuisance arthropods, further to environmental pollution (Singh et al., 2012). Using insecticides such as neonicotinoids may also be hazardous to the environment and beneficial arthropods, e.g., pollinators and predators, through direct and indirect exposure (Frank and Tooker, 2020). For instance, the farmers of Vadodara city in India mainly depend on organophosphates (Endosulphan™, Chlorpyriphos™, Parathion™), synthetic pyrethroids (Cypermethrin™, Deltamethrin™), and carbamates (Aldicarb™, Carbaryl™, Carbofuran™) are used for spraying the crops in the agricultural fields for the control of insect pests and to prevent the yield loss.

Although IPM has been advocated in India at least from the 1980s, only 3.2% of Indian farmers have adopted IPM practices in various crops. IPM research has changed Indian farmers' attitudes towards arthropod management in the last decade, resulting in reduction pesticide use by 20–100% in different crops (Rao and Rao, 2010). Effective monitoring of arthropods using traps, a basic measurement tool in the IPM can be achieved by directly sampling the arthorpod or through the use of sex-pheromone traps widely used to monitor populations of *Helicoverpa armigera* (Lepidoptera: Noctuidae), *Spodoptera litura* (Lepidoptera: Noctuidae), *Pectinophora gossypiella* (Lepidoptera: Gelechiidae), *Scirophagous incertulus* (Lepidoptera: Crambidae), species of Dynastinae (Coleoptera: Scarabaeidae), species of *Aproaerema* (Lepidoptera: Gelechiidae) in diverse crop ecosystems (Rao and Rao, 2010). Biorational pesticides include a range of product types with the general traits of being relatively non-toxic, with minimal side effects. These biorational approaches include the monitoring tools (e.g., physical traps, pheromone traps) are effective in indicating the population numbers of nuisance arthropods and thus are useful in applying as conventionally used pesticides as an integrated approach for pest management.

Use of sustainable agricultural practices, such as cultural-control farming, can be manipulated in a variety of ways including either early or delayed sowing, selection of the trap crops, altering plant density or arrangement, sowing genetic mixtures, and improved irrigation methods to reduce the impact of pestiferous arhropods. Farmers in Vadodara prefer the other technique, which involves cultural control practices such as crop rotation and crop residue removal (Kataria and Kumar, 2020). For instance, *Brassica* crops (Brassicaceae) are rotated with non-cruciferous crops, for example, *Cicer arietinum* (Fabaceae) and *Solanum tuberosum* (Solanaceae) to distract pestiferous arthropods, such as *Plutella xylostella* (Lepidoptera: Plutellidae), *Trichoplusia ni* (Lepidoptera: Noctuidae), *Brevicoryne brassicae* (Hemiptera: Aphididae), *Bemisia tabaci* (Hemiptera: Aleyrodidae). Mechanical management includes manual removal of the eggs and larvae of *Earias insulana* (Lepidoptera: Nolidae), *H. armigera*, and *S. litura*. Farmers utilize these simple and common practices to manage pestiferous arthropods. Some farmers prefer to use the high-speed water jets to wash off small insects such as the species of *Aphis* (Hemiptera: Aphididae), species of *Thrips* (Thysanoptera: Thripidae). On the other side, BioLure® (Suterra Monitoring Solutions, USA) have the potential of trapping (around 1000 eggs/trap). In addition, the use of Trichocards™ as a measure of biological management is popular among Vadodara farmers for managing populations of *H. armigera* and *S. litura*. Farmers place Trichocards™ stapled to the abaxial surface of the leaf usually in the mornings, to avoid direct sunlight. These Trichocards™ are released into the fields of species of *Gossypium*, *B. oleracea*, *Ricinus communis* (Euphorbiaceae), where species of *Trichogramma* (Hymenoptera: Trichogrammatidae) parasitise eggs of the infesting Lepidoptera and kill them. Five to eight cards/ha are usually placed, with each card including *Corcyra cephalonica* 1000 eggs. At the time when cards are released into the fields, spraying of insecticides is not recommended (Kataria and Kumar, 2020).

B. IPM challenges and adoption barriers

Implementation of IPM is full of challenges, especially in developing countries. India has 15 agro-climatic regions, based on soil types, rainfall, temperature, humidity, and hydraulics, which influence the cropping systems. The major challenges in implementing IPM programmes and adopting the new techniques in IPM practices are closely linked to policy, social and psychological factors, training and knowledge, and extension methods. The central government should implement a supportive policy for alternative management practices to regulate pestiferous insects. Psychological and social barriers must be carefully considered by farmers and those implementing IPM practices. The delivery of new technologies is crucial and the nature of IPM requires participation calling for a paradigm shift in e xtension methods. IPM implementation also faces the constraints of training and knowledge experienced chiefly by farmers and extension agents. Because of the difficulties in implementing IPM, extension organizations and agencies must play a larger role in educating farmers about the new methods and practices. The DAC & FW in the Union Ministry of Agriculture and Farmers' Welfare promotes IPM approach under the scheme 'Strengthening and Modernization of Pest Management Centres' in 28 states and union territories.The mandate for these centres is pest, disease monitoring, production and release of biological-control agents, conservation of biological-control agents and human-resource development in IPM by imparting training to agricultural extension officers and farmers at the grassroot level by organizing Farmer's Field School.

The Central Integrated Pest Management Centres (CIPMC) in different parts of India are involved in implementation of various eco-friendly plant-protection approaches approved by the Government of India. The CIPMCs carryout various tasks assigned to them periodically to promote sustainable plant-protection approaches. They are conducting season- long training programme of 30 days on IPM and popularizing IPM among farmer community on an annual basis. There are mechanisms to evaluate the success of programmes implemented by the CIPMCs centers. These extensions programmes play a key role in educating farmers about the ecology of pestiferous arthropods and new techniques developed in IPM. The extension organizations cannot address the difficulties of IPM on their own, since they require assistance from other stakeholders. The other challenges include a lack of awareness and innovation among extension personnel and target groups, insufficient cooperation between research and extension agencies, problem of timely and adequate supply of quality inputs, including biocontrol agents and biopesticides, complexity of IPM vs simplicity of chemical pesticides, dominant influence of pesticide industry, non-availability of location specific IPM modules for many crops.

Most of the private, corporate enterprises do not support shifting away from chemical pesticides to biopesticides because use of biopesticides would be less remunerative to them. Public-sector enterprises now hold only 2% of the biopesticide market share. To take advantage of new prospects and address global environmental concerns, the commercial sector needs to transition to biopesticides.The wide adaptability of IPM still remains a question, because of its acceptability in field conditions. Taking economic returns into account of IPM, farmers are confused, whether to accept it or not. To promote IPM, it is necessary to have many field demonstrations offered at the farmer's level. There is hardly any data available on the adoption of IPM in India. According to biopesticide production figures, IPM is predicted to cover 19% fungicides and 17% herbicides of gross cultivated area under IPM.

Resistance to change is widely prevalant in accepting IPM. Biopesticides are slow in action compared with chemical pesticides. Farmers may find it challenging to manage IPM on their own. If IPM needs to be promoted, it would be better to promote it as a community-centric method. Community-centric approach should be followed in India for a better appreciation and wider adoption of IPM. The essential requirements for implementing IPM are as follows: the availability of location-specific IPM modules, which are ecologically sound, economically viable and socially acceptable, area-wide dissemination strategy, high level of target group participation, removal of obstacles in the dissemination of IPM, measuring, evaluating, and publicizing the impacts of IPM. The conservation of natural enemies of pestiferous arthropods and their augmentation is of prime importance. Besides, the intrinsic properties of renewability, reversibility, and resilience of botanicals and biopesticides make them the most dependable tools for sustainable IPM. Hence, to maintain ecological balance and concurrently to manage pestiferous arthropods within thresholds, the use of bio-agents and biopesticides/botanicals should receive priority attention.

C. Augmentative use of predators and parasitoids

Several IPM programs opted in India include the release of insectary-reared parasitoids, or predators in agricultural fields to manage pestiferous insects. The Coccinellidae are the most useful predators in the IPM context. More than 5,200 species have been described worldwide in the Coccinellidae (Boopathi et al., 2020; Hodek et al., 2012). About 90% of approximately 4,200 species of the Coccinellidae are beneficial because of their predatory behaviour, mostly against the Hemiptera and Acarina (Awasthi et al., 2013). Biological management is a sound substitute for toxic insecticides, because biological management not only protects plants, but human beings and the environment as well (Boopathi et al., 2020). There are several habitats where the Coccinellidae occur (Hodek et al., 2012). They feed on sap sucking arthropods such as Aphidoidea, Coccoidea, Thysanoptera, and Acarina (Boopathi et al., 2020).

Harmonia axyridis Pallas (Coleoptera: Coccinellidae) is a popular biomanagement agent for greenhouse pestiferous insects, such as the species of *Aphis*, *Thrips* and *Bemisia*, but has become a serious invasive (Ukrainsky and Orlova-Bienkowskaja, 2014). Sporadic occurrence of *H. sedecimnotata* (Coleoptera: Coccinellidae) has recently been reported in India (Boopathi et al., 2020). Most of H. sedecimnotata occur on *Abelmoschus esculentus* (Malvaceae), *Solanum melongena* (Solanaceae), *Capsicum annuum* (Solanaceae), *Solanum lycopersicum* (Solanaceae), *Psidium guajava* (Myrtaceae) (Boopathi et al., 2020). The releases of the Coccinellidae are used to manage various species of the Aphidoidea infesting species of *Gossypium*, *S. tuberosum*, and *S. melongena* (Long and Finke, 2014). Polyphagous and predatory Coccinellidae who indiscriminately feed on diverse Aphidoidea on plants such as *A. esculentus*, *S. melongena*, *C. annuum* exhibit variations in fitness, and are therefore likely to vary in their genotypes. An important source for biological control agents will be the most effective genotypes of a predator species with a high predation potential (Boopathi et al., 2020). Boopathi et al. (2020) reported that inoculative release of 30-50 adults (both males and females)/ 100 m^2 achieved a reduction up to 90%, of the infesting Aphidoidea. Thus, it may be recommended the release rate of 40 adults/ 100 m^2 to suppress *Aphis gossypii* populations on *S. melongena*. *Harmonia sedecimnotata* is, therefore, a highly promising biological management agent for *A. gossypii* populations that can be achieved for rapid management through inoculative release of adults. Factors that affect the ability of releases of the Coccinellidae to result in rapid reduction in populations of the Aphidoidea in greenhouses include either repeated releases or increased numbers released predatory adults (Riddick, 2017).

Predators used augmentatively for biological management include different species of *Coccinella* (Coleoptera: Coccinellidae), *Chrysoperla* (Neuroptera: Chrysopidae), Staphylinidae (Coleoptera), Syrphidae (Diptera), Reduviidae (Hemiptera), and *Phytoseiulus persimilis* (Mesostigmata: Phytoseiidae).The other success stories in biological management include the management of *Pyrilla perpusilla* (Hemiptera: Lophopidae) was the utilization of egg parasitoids such as *Tetrastichus pyrillae* (Hymenoptera: Eulophidae) and ectoparasitoids *Epipyrops melanoleuca* (Lepidoptera: Epipyropidae) in subtropical india (Gangwar et al., 2008). *Eriosoma lanigerum* (Hemiptera: Aphididae) and *Quadraspidiotus perniciosus* (Hemiptera: Diaspididae) inflict damage to different species of *Malu*s (Rosaceae) plantations and have been successfully controlled by their biological management agents. *Aphelinus mali* (Hymenoptera: Aphelinidae), *Syrphus confrater* (Diptera: Syrphidae) and *Chrysopa scelestes* (Neuroptera: Chrysopidae) have been highly useful in regulating populations of *E. lanigerum*, whereas *Encarsia perniciosi* and species of *Aphytis* (Hymenoptera: Aphelinidae), *Chilocorus bijugus* (Coleoptera: Coccinellidae) were relevant in the instance of *Q. perniciosus*. *Ceratovacuna lanigera* (Hemiptera: Aphididae) was successfully managed by applying *Dipha aphidivora* (Lepidoptera: Pyralidae), species of *Chrysoperla*, diverse Coccinellidae (Coleoptera) and Syrphidae (Diptera); and various arachnids (Araneae) were not helpful in the states of Maharastra and Karnataka in 2003-2004. *Helicoverpa armigera*, a polyphagous pestiferous arthropod, was successfully managed with the use of nuclear polyhedrosis virus (NPV) on species of *Gossypium*, *Phaseolus*, and *Glycine* (Fabaceae), and *C. annuum* in India (see weblinks of DPPQS, Government of India, 2005).

Trichogramma chilonis and *T. japonicum* (Hymenoptera: Trichogrammatidae) are widely used in India presently to manage various Lepidoptera that attack *Oryza sativa* and *Saccharum officinarum* (Poaceae), various species of *Bracon* (Hymenoptera: Braconidae), *B. hebetor*, *B. brevicornis*, *Chelonus blackburnii* (Hymenoptera: Braconidae) to regulate populations of several pestiferous Lepidoptera, such as *Earias vitella* (Lepidoptera: Nolidae), *Phthorimaea operculella* (Lepidoptera: Gelechiidae), *P. gossypiella* and *H. armigera* on species of *Gossypium*, *S. tuberosum,* and many other plants. *Goniozus nephantidis* (Hymenoptera: Bethylidae) is widely used to manage populations of *Opisina arenosella* (Lepidoptera: Xyloryctidae). *Goniozus nephantidis* is being mass multiplied and released in Karnataka and Kerela. Parasitoids include various species of the Tachinidae (Diptera) and other Hymenoptera, e.g., *Acerophagus papayae* (Encyrtidae) that are being used to regulate populations of *Paracoccus marginatus* (Hemiptera: Pseudococcidae). Shendage and Sathe (2015) have reported that many Tachinidae attack close to 20 pestiferous insects in Kolhapur region. However, no culture method for commercial mass production of the Tachinidae is available in India. Therefore, the augmentative application of the Tachnidae in pestiferous arthropod management is limited. A maximum of 40% and minimum of 2% parasitism was recorded on *S. litura* and a species of *Forficula* (Dermaptera: Forficulidae) and by Tachinidae macrotype egg parasitoids, respectively. For instance, species of *Exorista* (Diptera: Tachinidae) parasitize *H. armigera* and *S. litura*. *Exorista larvarum* (Diptera: Tachnidae) is a Palaearctic species widely distributed in several Asian regions. About 15 lepidopteran families are known hosts for *E. larvarum*. *Exorista japonica* occurs widespread from India to East Asia, and 18 lepidopteran families are recorded as its hosts. The known natural hosts for both species belong mainly to the Lymantriidae, Lasiocampidae, Noctuidae and Arctiidae (Dindo and Nakamura, 2018). *Aphidius colemani* (Hymenoptera: Braconidae) is a solitary, koinobiont endoparasitoid of the Aphidoidea, and is one highly sought after agent to manage pestiferous arthropods that infest greenhouse plants. A natural parasite, *A. colemani* is mainly used to regulate the economically important *Myzus persicae* (Hemiptera: Aphididae) and *A. gossypii*. These Aphididae are highly polyphagous and attack a wide range of vegetable and ornamental crops especially in greenhouses. *Aphidius colemani* can maintain the Aphididae populations at levels similar to those resulting from pesticide applications (Pardo et al., 2015).

Augmentative release of the parasitic Hymenoptera in greenhouses has been used in different parts of the world (Fahrat and Dharmadhrt, 2021). *Aphelinus asychis* Walker (Hymenoptera: Aphelinidae), *A. matricariae* Haliday and *A. ervi* Haliday (Hymenoptera: Braconidae) have been identified to parasitize *M. persicae* infesting *C. annuum* (Fahrat and Dharmadhrt, 2021). Khan et al. (2020) have reported that more than one species of *Trichogramma* are effective biological control agents, functioning as egg parasitoids. It is a fact that these parasitoids were exploited for controlling the several pestiferous insects belonging to the Coleoptera, Hymenoptera, and Lepidoptera. More than 240 species are known, of which 45 are recorded from India. The successful implementation of an augmentative biological control programme requires a thorough understanding of the biology of the pestiferous arthropod, its natural enemies, the crop environment (including other nuisance organism management practices). The success of this approach is dependent on many considerations, that may necessitate modifications of current production practices and management practices.

D. Microbial and botanical pesticides

Biological control offers a better alternative to synthetic chemical pesticides, because biopesticides of either microbial or botanical origin are target specific, with easy biodegradability, shorter life-span, and user friendly in sustainable agriculture (Chattopadhyay et al., 2017). About 100 species of bacteria are presently known as exo- and endo-pathogens of arthropods (Chattopadhyay et al., 2017). But only a few of them are commercially available (Chattopadhyay et al., 2017). Multiple activities of biopesticides are now considered under integrated crop management (ICM). For example, *Serratia entomophila* AB2 (Enterobacteriaceae) reported from epizootic species of *Heliothis* exhibited both fungicidal and nutrient-solubilizing ability (Chattopadhyay et al., 2017). In a few instances, nuclear polyhedrosis virus (NPV) is used as target-specific products, such as NPV for *H. armigera* (HaNPV) and *S. litura* (SlNPV) used to regulate populations of *H. armigera* and *S. litura* in *Gossypium* (Mondal et al., 2021).

Biopesticides are an essential component of IPM programmes to manage pestiferous arthropods thriving on several economically important fruits and vegetables. Globally there were approximately 700 products in this category, based on 175 different active ingredients (Mishra et al., 2018). In India, 15 biopesticides are currently registered of which five bacteria and include *Pseudomonas fluorescens* (Pseudomonadaceae) and four species of *Bacillus* (Bacillaceae), three fungi which include two species of *Trichoderma* (Hypocreaceae) and a species of *Beauveria* (Cordycipitaceae), and two are NPV against *H. armigera* (HaNPV) and *S. litura* (SlNPV), and two include botanicals from *Azadirachta*

Table 1. List of commercially available biopesticides registered in India (Anonymous, 2014)

Biopesticide	Microorganism	Useful in the management of
Bacillus thuringiensis var. *israelensis*	Bacterium	*Plutella xylostella*
Bacillus thuringiensis var. *kurstaki*	Bacterium	*Plutella xylostella*
Bacillus thuringiensis var. galleriae	Bacterium	*Helicoverpa armigera*
Bacillus sphaericus	Bacterium	*Plutella xylostella*
Bacillus firmus	Bacterium	*Plutella xylostella*
Bacillus subtilis	Bacterium	*Diabrotica virgifera*
Trichoderma viride	Fungus	Species of *Fusarium*
Trichoderma harzianum	Fungus	*Fusarium oxysporum*
Pseudomonas fluorescens	Bacterial/ Fungal	Species of *Bemisia*
Beauveria bassiana	Entomopathogenic fungus	*Idioscopus clypealis* Species of *Phenococcus* and *Maconellicoccus* Species of *Hypothenemus*
Paecilomyces lilacinus	Fungus	Species of *Meloidogyne*
Verticillium lecanii	Fungi	*Bemisia tabaci, Myzus persicae*
Verticillium chlamydosporium	Nematophagous fungus	Species of *Meloidogyne*
Metarhizium anisopliae	Entomopathogenic fungus	*Spodoptera litura,* species of *Coptotermes*, *Odontotermes*
NPV of *Helicoverpa armigera*	Virus	*Helicoverpa armigera* living on *Cicer arietinum*
NPV of *Spodoptera litura*	Virus	*Spodoptera litura*
Neem based biopesticides	Plant product	Species of *Bemisia*
Cymbopogon	Plant product	*Agrotis ipsilon*
Heterorhabditis bacteriophora	Entomopathogenic nematodes	Speies of *Leptinotarsa*
Species of *Trichogramma*	Egg parasitoid	Species of *Diatrea*
Fenpyroximate	Pyrazole acaricide	*Tetranychus urticae*

indica (Meliaceae) and *Cymbopogon flexuosus* (Poaceae) (Mishra et al., 2018) (Table 1). Among biopesticides, those including *Bacillus thuringiensis* (Bt) (Bacillaceae), *Trichoderma viride* (Hypocreaceae), species of *Metarhizium* (Clavicipitaceae), *Beauvaria bassiana* (Cordycipitaceae), and various nuclear polyhedrosis viruses (NPV) (Baculoviruses) affecting insects, predominately the plant-damaging Heterocera and Rhopalocera (Lepidoptera). Microbes such as *Lecanicillium lecanii* (Cordycipitaceae), *Paecilomyces lilacinus* (Ophiocordycipitaceae), *Pochonia chlamydosporia* (Clavicipitaceae), *Nomuraea rileyi* (Clavicipitaceae) are considered entomopathogenic fungi, registered with the National Bureau of Agricultural Insect Resources (NBAIR), Bengaluru. Azadirachtin and pyrethrins are widely used. Pyrethrin from *Tanacetum cinerariifolium* (Asteraceae) is known for its potent insecticidal and repellent activity but is relatively less known for use in plant protection (Kachhawa, 2017). Ramasamy et al. (2020) evaluated different microbials useful as pesticides and neem-compounds either singly or in combination (sequential application) against major insect pests such as *P. xylostella* on *Brassica juncea* (Brassicaceae) in different provinces of Cambodia, suggesting that they might be compatible with other plant protection options such as biopesticides viz., fungicides and bactericides.

The economic feasibility and environmental compatibility of microbial or botanicals as tools facilitating sustainable agriculture is well demonstrated presently (Fenibo et al., 2021). Consequently, the use of conventional pesticides in commercial farming is attracting regulatory restrictions leading to 2% decline/year in synthetic pesticide use in favour of 10% increase in biopesticides as alternative agrochemicals (Fenibo et al., 2021). Microbial pesticides, biochemical pesticides, and plant incorporated protectants (PIPs) are the well known categories of biopesticides, and they fill 5% share of the pesticide global market, with microbial biopesticide taking the lead (Fenibo et al., 2021). Muzemu et al. (2011) reported more than 50% reduction of *B. brassicae* and *Tetranychus evansi* (Acarida: Tetranychidae) populations by applying leaf powder extract of *Lippia javanica* (Verbenaceae) and *Solanum campylacanthum* (Solanaceae) to replace pesticides by 100% and go for total adoption of biopesticides. However, total adoption of biopesticides is hindered by short supply of products, high cost, and slow action. These drawbacks are mostly offset by the tolerable toxicity, if any, that is displayed by biopesticides. They are also biodegradable, target specific, and can counter pestiferous insects' resistance that generally arise when synthetic pesticides are used (Fenibo et al., 2021).

Microbial insecticides include a microorganism, which could be either a bacterium or a fungus or a virus or a protozoan or an alga as the active component (Kachhawa, 2017). Microbial insecticides can help in controlling many pestiferous arthropods, although each active microbe is usually specific for a target organism (Vikas et al., 2014). For example, *B. bassiana* is an entomopathogenic fungus that kills *H. armigera*, *S. litura*, *P. xylostella*. *Lecanicillium lecani* (Cordycipitaceae) is used to manage populations of *B. tabaci*. The most widely known microbial pesticides are those developed involving strains of *Bt*, which can manage insects attacking *B. oleracea*, *S. tuberosum*, species of *Gossypium*, *Zea mays* (Poaceae), *Nicotiana tabacum* (Solanaceae) and *Glycine max* (Fabaceae) via Cry proteins. To ensure that microbial pesticides do not affect the non-target species, they need to be regularly monitored. Bt-based pesticides are presently considered a crucial component in IPM programmes.

Entomopathogenic fungi such as *B. bassiana* and species of *Metarhizium* are useful in controlling pestiferous Aphidoidea, such as *M. persicae* and *A. gossypii* (Vu et al., 2007), Termitoidea viz., species of *Odontotermes* (Isoptera) (Ambele et al., 2020) and the Lepidoptera viz., *S. litura* (Malarvannan et al., 2010). Nuclear polyhedrosis viruses could possibly used to regulate populations of critical and major pestiferous arthropods such as *H. armigera* and species of *Spodoptera*. da Costa et al. (2019), isolated three isolates of nucleopolyhedrosis viruses from *H. armigera* and compared them genetically and biologically to Gemstar® (polyhedral occlusion bodies of the nuclear polyhedrosis virus of *H. zea*). They reported the genetic sequencing of lef-8 and lef-9 genes, which revealed that the Brazilian isolates were closely related to the nucleopolyhedrosis virus from Australia, South Africa, China and India. The isolates inflicted high rates mortality in third instar larvae of *H. armigera*. The high degree of relatedness among the Brazillian *H. armigera* virus isolates and those of Australia (HearNPV-Aus), China (HearNPV Complete Genome), and South Africa (HearNPV-Nng-1) suggest the highly specific baculovirus infecting *H. armigera* globally. *Bt* is widely used against pestiferous arthropods infesting species of *Gossypium* and vegetable crops such as *S. melongena*, *S. tuberosum*, and *B. oleracea*. Various genetically modified plants, such as *Bt* cotton, corn, tabacco, soybean, maize that produce *Bt* proteins enable the microbial pesticides widespread commercial use. RNAi is a novel and potential tool to develop further pestiferous insect management, targeting various orders of insects including Diptera, Coleoptera, Lepidoptera, Hymenoptera, and Isoptera. Nitnavare et al. (2021) reported that dsRNA are effective against the pestiferous beetles such as *Diabrotica virgifera virgifera* (Coleoptera: Chysomelidae).

Various techniques for an effective oral administration of dsRNA into the gut of insects have been explored. Another technology is the use of nanoparticles as carrier of dsRNA through to insect-gut epithelia. Several nanoparticle systems have been used for this purpose including liposomes, chitosans, and branched amphiphilic peptide capsules (BAPCs) in the Lepidoptera, Coleoptera, Diptera, and Dictyoptera. Silencing efficacies vary among the insect classes wherein the Coleoptera often exhibit 100% susceptibility and the Hemiptera exhibit lesser susceptibility. Lepiodoptera are the most recalcitrant to oral RNAi owing to their highly alkaline gut. These techniques are being gradually accepted in India presently the host-delivered amiRNA-mediated silencing *HaAce1* gene is used for *H. armigera* management (Saini et al., 2018). One limitation of RNAi as a pestiferous insect-management tool is that the target insect must consume a significant dose of dsRNA to be killed; as a result, delivery systems that make such acquisitions possible must be created (Isman, 2019). India has adequate facilities to focus on the development of a product based on nanotechnology based RNA editing and CRISPR/Cas9 mediated genome editing. Several transgenic plants were developed in India, such as *G. max*, *Z. mays*, species of *Gossypium*, and *Brassica napus*. Shelton (1999) worked on the first field release of a genetically engineered insect virus for insect control. In 2017, cooperating with colleagues at the UK-based Oxitec Limited, the first release of a genetically engineered pestiferous insect, *P. xylostella* strain (OX4319L) with a self-limiting gene to control the spread of *P. xylostella* was conducted. In 2015-2020, Shelton was involved with the introduction of *Bt S. melongena* in Bangladesh and the Philippines. A recent study confirmed that *Bt S. melongena* dramatically reduces insecticides, and that growers receive an average of 19.6% higher yield and 21.7% higher revenue than non-*Bt* varieties. On a per tonne basis, the revenue benefit of using *Bt S. melongena* was 1.7% reflecting different level of acceptability among trade buyers and consumers. Some farmers were prepared to pay higher prices for *Bt S. melongena,* because the fruit was less damaged while others paid a price discount because the *Bt S. melongena* was not available in preferred local varieties. Furthermore, the study confirmed that *Bt S. melongena* is accepted in the market (Shelton et al., 2020); but an idea of introducing and cultivation *Bt S. melongena* was summarily rejected by Government of India in 2010 after several public debates.

Trichoderma species (Hypocreaceae) have been widely used in agriculture. For instance, *T. harzianum* and *T. viride* are the widely used species in India and have been exploited on about 87 different crops. *Trichoderma* acts directly as an entomopathogen through parasitism and the production of insecticidal secondary metabolites, antifeedant compounds and repellent metabolites (Poveda, 2021). The efficacy of different species of *Trichoderma* as an entomopathogen and their effects on various arthropods is summarized in Table 2. On the other hand, the species *T. viride* and *T. citrinoviride* have been reported with the ability to produce different compounds with antifeedant activity against different insects. For example, *T. viride* used to control the *Bombyx mori* (Lepidoptera: Bombycidae), *Corcyra cephalonia* (Lepidoptera: Pyralidae), *H. armigera* and the volatile organic compounds (VOCs) produced is the chitinase. *Trichoderma citrinoviride* used to control the *Schizaphis graninum* (Hemiptera: Aphididae), *Acanthoscelides obtectus* (Coleoptera: Chrysomelidae) and the VOCs produced are citrantifidiene, citrantifidiol and bisorbicillinoids that are capable of repellence. Furthermore, several species of *Trichoderma* (*T. harzianum*, *T. viride* and *T.*

Table 2. Efficacy of species of *Trichoderma* (Hypocreaceae) on pestiferous insects

Ecology	Species	Pestiferous insects	Mortality (%)	References
Parasitic	*T. longibrachiatum, T. harzianum*	*Bemisia tabaci*	90% mortality in 14 days	Zahran et al., 2017
		Oryctes rhinoceros	90% mortality in 14 days	Nasution et al., 2018
		Acanthoscelides obtectus	90% mortality in 14 days	Rodriguez-Gonzalez et al., 2020
		Xylotrechus arvicola	90% mortality in 14 days	Rodriguez-Gonzalez et al., 2017
	T. album	*Rhyzopertha dominica*	94% mortality in 7 days	Mohamed and Taha, 2017
	T. longibrachiatum	*Leucinodes orbonalis* (Lepidoptera: Crambidae)	Increase crop yield and causing up to 50% mortality	Ghosh and Pal, 2016
Secondary metabolites	*T. atroviride*	*Drosophila melanogaster*	Prevent feeding and effect the development and survival of larvae	Hernandez et al., 2019
Peptaibols	*T. harzianum*	*Tenebrio molitor*, *Tribolium castaneum, Schizaphis graminum*, *Diuraphis noxia A. gossypii, Amrasca biguttula biguttula*	Mortality rates of 100% in 15 days	Ganassi et al., 2001; Rahim and Iqbal, 2019; Nawaz et al., 2020
Secondary insecticidal metabolites	Species of *Trichoderma*	*Locusta migratoria, Earias insulana, Pectinophora gossypiella*	Mortality percentage reduced to 50% in 3 days	El-Massry et al., 2016

citrinoviride), whose VOCs act as repellants for pestiferous insects, have scope for reducing damage to plants.

Microorganisms based pesticides and their by-products are widely used in pestiferous insect management tactics because they are effective, species-specific and environmentally friendly (Koul, 2011). The microbial biopesticide market constitutes about 90% of total biopesticides including *Bt* in GM plants, and there is ample scope for further development in agriculture. However, there are challenges as well (Koul, 2011). There are at least 1500 naturally occurring insect-specific microorganisms, of which 100 are considered insecticidal (Koul, 2011). More than 200 microbial biopesticides are available in 30 countries affiliated to the Organization for Economic Cooperation and Development (Koul, 2011). There are 53 microbial biopesticides registered in the USA (2006), 22 in Cananda and 21 in the European Union (Skula et al., 2019); although reports of the products registered for use in Asia are lacking (Skula et al., 2019).

Plant-derived products in some instances have been shown to be effective against certain pestiferous insects (Tembo et al., 2018). Several hundred candidate plant species and compounds are now known to have pesticidal properties against a range of pestiferous arthropods. Despite this growing body of information, only a few natural products are commercialized in pestiferous-arthropod management (Tembo et al., 2018). Tembo et al. (2018) reported that plant extracts were used to manage pestiferous insects of various legumes without harming beneficial arthropods. Botanical pesticides repel pestiferous arthrtopods, modify insect behaviour, and may include antifeedant compounds (Singh et al., 2012). In addition, extracts from *Origanum vulgare*, *Thymus vulgaris* (Lamiaceae) and *Trachyspermum ammi* (Apiaceae) showed broad spectrum of antifungal activity against *Tribolium castaneum* (Coleoptera: Tenebrionidae) (Bhavya et al., 2020). Leaves of the species of *Eucalyptus* (Myrtaceae) include many terpenoids such as α- and β-pinene, 1,8-cineole (CIN), terpineol, and globulol, which are useful as fumigants against some stored grain and other pestiferous insects (Fatemeh and Moharramipour, 2017). Botanical insecticides are currently used to control certain pests and details are metioned in Table 3.

E. Semiochemicals used in IPM

Semiochemicals are popular and well accepted in developed countries, but only 7-10 pheromonal lures are presently available in India. Semiochemicals are organic compounds produced by either insects or plants that transmit chemical messages within or between populations. Insects detect semiochemicals from the air because of olfactory receptors on their antennae. As a broad group, semiochemicals include pheromones and allelochemicals (that include kariomones). Pheromones are further divided based on the responses they elicit as sex, alarm, aggregation, and

Table 3. Botanicals used currently to manage arthropods

Botanical	Plants	Arthropods	References
Pyrethrins (pyrethrum, pyrenone)	*Chrysanthemum cinerariaefolium*	*Frankliniella occidentalis*	Yang et al., 2012
Rotenone	Species of *Lonchocarpus, Derris*	*Spodoptera litura*, *Plutella xylostella*	Zubairi et al., 2016
Nicotine	Species of *Nicotiana*	*Grapholita molesta*	Sarker and Lim, 2018
Veratine	*Schoenocaulon officinale*	*Scirtothrips citri*	Godfrey et al., 2005
Ryanodine	*Ryania speciosa*	*Leptinotarsa decemlineata,* Species of *Corythucha*, *Aphis*, *Anasa*	Souto et al., 2021
Limonene	Species of *Citrus*	Species of Pseudococcidae	Hollingsworth, 2005
Neem-based formulations (Small-scale formulators)	*Azadirachta indica*	*Melanotus communis*	Humbert et al., 2017
Neem oil (Bioactive i.e., Limonoids, Nimbin, Salannin, Nimbinin)	*Azadirachta indica*	*Tribolium castaneum, Sitophilus zeamais*	Kumar et al., 2022
Neem seeds, Neem fruit powder extract (NFPE)	*Azadirachta indica*	*Plutella xylostella,* species of *Aphis*	Rao and Rao, 2010

trail pheromones (Fig. 2). Kairomones are chemicals whose detection is advantageous to the receiver, but not to the emitter. Kairomones guide arthropod predators and parasitoids to their hosts or prey. These semiochemicals are used in various insect control strategies such as in monitoring, in mass trapping, to attract and kill approach, and in mating disruption, and as feeding deterrents (Heuskin et al., 2011). Repellants such as verbenone ($C_{10}H_{14}O$), an insect phereomone analogue occurs in a variety of plants, but more commonly in *Salvia rosemarinus* (Lamiaceae), and *Aloysia citriodora* (Verbenaceae) can be used for controlling populations of *Dendroctonus frontalis* and *D. ponderosae* (Coleoptera: Curculionidae) (Fettig and Munson, 2020), and *Xyleborus glabratus* (Coleoptera: Curculionidae). Some parasitoids, such as *Anagyrus* sp. nov. nr *pseudococci* (Hymenoptera: Encyrtidae) are attracted by the sex pheromones of their target hosts, which act as kairomones for the parasitoids (Franco et al., 2008).

More than 3000 compounds that act as semiochemicals for various insects have been determined. Semiochemicals have been used for pestiferous-arthropod management for more than 100 years. Insect sex pheromones are widely used for monitoring of some species of the Lepidoptera and Coleoptera. The different types of pestiferous arthropods have been successfully managed by employing various semiochemicals (Table 4). Semiochemicals are safe and environmentally friendly because of their natural origin, low persistence in the environment, high species specificity, lack of residues, and safety to non-target organisms. However, there are some difficulties in the practical use of semiochemicals in pestiferous-arthropod management. Pheromone components that either promoted or hindered adoption for pestiferous arthropod management have included biological differences in mate-finding behaviour of different species, complications of chemistries involved, challenges in producing the controlled-release dispensers, and the discovery of effective trap designs. In addition, the political, economic, and use-patterns, particularly in governments regulations of pheromone application make them challenging. In India, the focal pestiferous arthropod species where semiochemicals are playing a major role in IPM programmes are limited. It is largely confined to the Tephritidae through male annihilation technique (MAT) on *Mangifera indica* (Anacardiaceae), species of Cucurbitaceae, and other crops viz., *P. guajava* (Myrtaceae), species of *Citrus* (Rutaceae). No serious efforts have been made about chemo-behavioural strategies of the Tephritidae in India involving host kairomones and male-based

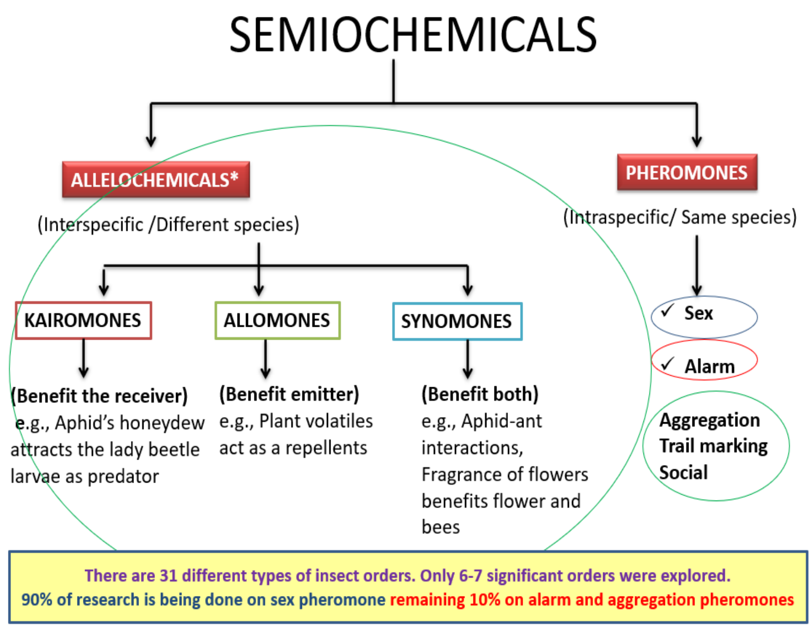

Fig. 2. Semiochemicals in IPM- In agricultural settings, sex, alarm, repellent and aggregation pheromones have been employed for monitoring, mass trapping, male annihilation techniques and auto-confusion. Only few allelochemicals are employed for pestiferous arthropod management, remainder need to improve.*Allelochemicals can be further sub-divided into three groups – kairomones, allomones and synomones (bluish-green circle line).

Table 4. Examples of pestiferous arthropods successfully managed employing various semiochemicals

Pheromones	Compounds	Pestiferous arthropod	References
Aggregation pheromones	$^{+}$neryl(S)-2-methylbutanoate, (R)- lavandulyl acetate, $^{+}$(R)-lavandulyl-3-methyl-3-butenoate	*Frankliniella occidentalis, Thrips palmi* Various Cerambycidae (Coleoptera) *D. ponderosae*	Kirk, 2017
	4,6,6-trimethylbicycle [3.1.1.] hept-3-en-2-one, Verbenone	*Rhynchophorus ferrugineus*	Silva et al., 2017 Fettig and Munson, 2020
	4-methyl-5-nonanol and 2,4-methyl-5-nonanone (9:1), Ethyl-4-methyl octanoate		Chakravarthy et al., 2014
Sex pheromones	dodecan-1-ol acetate, (Z)-7-dodecen-1-ol acetate, 11-dodecen-1-ol acetate, (Z)-9-tetradecenal, (Z)-9-tetradecen-1-ol acetate, (Z)-11-hexadecenal, and (Z)-11-hexadecen-1-ol acetate	*S. frugiperda*	Tumlinson et al., 1986
	(3E, 8Z, 11Z)-tetradecatrienyl acetate	*Tuta absoluta*	Ferrara et al., 2001
Attractants	Methyl eugenol (ME) and raspberry ketone	*Bactrocera dorsalis, B. curcurbitae*	Oliver et al., 2002
Putative sex pheromone	Lignoceryl acetate (24Ac), Lignocerol	*Diaphorina citri*	Zanardi et al., 2018

sex pheromones. Apart from the Tephritidae, the other important pestiferous arthropods affecting fruit trees where semiochemicals can play a key role in strengthening the existing IPM strategies are *Sternochetus mangiferae* (Coleoptera: Curculionidae), *Idioscopus* sp.(Hemiptera: Cicadellidae), *Deonalis albizonalis* (Lepidoptera: Crambidae), *Citripestis eutraphera* (Lepidoptera: Pyralidae), *Procontarinia matteiana* (Diptera: Cecidomyiidae), and *Erosomyia indica* (Diptera: Cecidomyiidae) (Jayanthi et al., 2015). Identifying potential semiochemicals for several Indian horticultural crop pests is still rudimentary.

Semiochemicals are marketed variously, including as pastes, sprays, and baits. Specialized pheromone and lure application technology (SPLAT), which was developed by ISCA technologies, Inc. (Integrated Pest Management Solutions for Sustainable Agriculture) in California, is used for the management of various pestiferous Lepidoptera and Coleoptera, such as *P. gossypiella*, *Anomala orientalis* (Coleoptera: Scarabaeidae), and *D. ponderosae*. In India, various field trials were conducted for *P. gossypiella* using auto-confusion techniques by the Hyderabad-based company ATGC Pvt. Ltd., collaborating with the Junagadh Agricultural University, Junagadh and University of Agricultural Sciences, Raichur. On the other side, SPLAT–Bloom is used to manage pollination by *Apis mellifera* (Hymenoptera: Apidae). Semiochemical technology needs more attention and research in the Indian subcontinent to move beyond this point of adoption. The IPM pheromone market is expected to grow at a CAGR of 12.3% from 2021 to 2028 to reach $1.54 billion by 2028.

Some of the volatile organic compounds emitted by microorganisms (MCOVs) and herbivore induced plant volatiles (HIPVs, stress volatiles) may be useful in managing inter- and intra-specific and tritrophic interactions in future (Aartsma et al., 2017). Microbial VOCs exhibit various biological properties beneficial for plant health, such as enhancing plant growth, inducing resistance against abiotic and biotic stress and inhibiting spore germination and mycelial growth of plant pathogens (Vlassi et al., 2020). Himanen et al. (2017) reported the role of VOCs of *Brassica* sp.in mediating and modifying insect behaviour and their potential in the development of VOC-based crop protection strategies combined with other established methods in the control of pestiferous insects. On the other hand, HIPVs are involved in plant communication with natural enemies of herbivorous insects, neighbouring plants, and different parts of damaged plant. The release of a wide variety of HIPVs in response to herbivore damage and their role in plant plant, plant herbivorous insect parasitoids, and intraplant communications represents a new facet of the complex interactions among different trophic levels. These volatiles are released from leaves, flowers, and fruits into the atmosphere or into the soil from roots in response to herbivore attack. Moreover, these volatiles act as feeding and oviposition deterrents to insect pests. These volatiles also mediate the interactions between the plants and the microorganisms. An overview of these volatiles emitted by plants, their role in plant defense against herbivores, and their implications for pestiferous insect management need to be exploited more.

CONCLUSIONS

Injudicious use of pesticides leads to a hazardous impact on the environment and humankind. To reduce their negative impact, alternative approaches need to be implemented in IPM and sustainable farming practice. Biologicals and biological controls, microbials and semiochemicals are used as useful and effective alternatives in IPM. However, while implementing these alternatives, farmers face several challenges. To overcome the challenges, adequate knowledge about the new techniques and ecology of pestiferous arthropods will need to be informed to farmers and other business stakeholders. Adequate support for plant protection research is essential to meet the challenges of producing healthy food from the available land with minimal adverse effects on the environment. This can be achieved through the development of a consortium approach involving international organizations, national agricultural research and extension systems, non-governmental agencies, and farmers in the research agenda to meet the needs.

ACKNOWLEDGEMENTS

The work is supported by USDA-ARS Research Project# 6066-22000-090-00D-Insect Control and Resistance Management in Corn, Cotton, Sorghum, Soybean, and Sweet Potato, and Alternative Approaches to Tarnished Plant Bug Control in the Southern United States.

Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

The U.S. Department of Agriculture prohibits discrimination in all its programmes and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programmes.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD). To file a complaint of discrimination, write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, S.W., Washington, D.C. 20250-9410, or call (800) 795-3272 (voice) or (202) 720-6382 (TDD). USDA is an equal opportunity provider and employer.

REFERENCES

Aartsma Y, Bianchi F J J, Werf W V D, Poelman E H, Dicke M. 2017. Herbivore-induced plant volatiles and tritrophic interactions across spatial scales. New Phytologist 216: 1054-1063.

Alwang J, Norton G, Larochelle C. 2019. Obstacles to widespread diffusion of IPM in developing Countries: Lessons from the field. Journal of Integrated Pest Management 10(1): 10; 1-8.

Ambele C F, Ekesi S, Bisseleua H D B, Babalola O O, Khamis F M, Djuideu C T L, Akutse K S. 2020. Entomopathogenic fungi as endophytes for biological control of subterranean termite pests attacking cocoa seedlings. Journal of Fungi 6(3): 126.

Awasthi N S, Barkhade U P, Patil S R, Lande G K. 2013. Comparative toxicity of some commonly used insecticides to cotton aphid and their safety to predatory coccinellids. The Bioscan 8(3): 1007-1010.

Bhagat S, Birah A, Chattopadhyay C. 2016. Crop health management: Perspectives in IPM. International Journal of Economic Plants 3(2): 070-073.

Bhavya M L, Chandu A G S, Devi S S, Quirin K-W, Pasha A, Vijayendra S V N. 2020. In-vitro evaluation of antimicrobial and insect repellent potential of supercritical-carbon dioxide (SCF-CO_2) extracts of selected botanicals against stored product pests and foodborne pathogens. Journal of Food Science Technology 57(3): 1071-1079.

Boedeker W, Watts M, Clausing P, Marquez E. 2020. The global distribution of acute unintentional pesticide poisoning: estimations based on a systematic review. BMC Public Health 20, Article no. 1875.

Boopathi T, Singh S B, Dutta S K, Dayal V, Singh A R, Chowdhury S, Ramakrishna Y, Aravintharaj R, Shakuntala I, Lalhruaipuii K. 2020. *Harmonia sedecimnotata* (F.): Predatory potential, biology, life table, molecular characterization, and field evaluation against *Aphis gossypii* Glover. Scientific Reports 10, Article no. 3079.

Chattopadhyay P, Banerjee G, Mukherjee S. 2017. Recent trends of modern bacterial insecticides for pest control practice in Integrated crop management system. 3Biotech 7(1): 60.

Dhaliwal G S, Jindal V, Mohindru B. 2015. Crop losses due to insect's pests: global and Indian scenario. Indian Journal of Entomology 77(2): 165-168.

Dindo M L, Nakamura S. 2018. Oviposition Strategies of Tachinid Parasitoids: Two *Exorista* Species as Case Studies. International Journal of Insect Science 10(1): 1179543318757491.

Duarte da Costa V H, Soares M A, Dimate F A R, Mendes de Sa, V G, Zanuncio J C, Valicente F H. 2019. Genetic Identification and Biological Characterization of Baculovirus Isolated from *Helicoverpa armigera* (Lepidoptera: Noctuidae) in Brazil. Florida Entomologist 102(1): 59-64.

Fahrat A, Dharmadhrt R. 2021. Potential role of *Aphidius ervi* in protecting greenhouse bell pepper cultures from *Myzus persicae* aphids in India. bioRxiv 1-4.

Fatemeh H, Moharramipour S. 2017. Chemical composition and antifeedant activity of essential oil from *Eucalyptus camoldulensis* and *Callistemon viminalis* on *Tribolium confusum*. International Journal of Agricultural Technology 13(3): 413-424.

Fenibo E O, Ijoma G N, Matambo T. 2021. Biopesticides in Sustainable Agriculture: A Critical Sustainable Development Driver Governed by Green Chemistry Principles. Frontiers in Sustainable Food Systems 5: 619058. doi: 10.3389/fsufs.2021.619058

Fetting C J, Munson A S. 2020. Efficacy of verbenone and a blend of verbenone and non-host volatiles for protecting lodgepole pine from mountain pine beetle (Coleoptera: Curculionidae). Agricultural and Forest Entomology 3: 1-6.

Franco J C, Silva E B, Cortegano E, Campos L, Branco M, Zada A, Mendel Z. 2008. Kairomonal response of the parasitoid *Anagyrus* spec. Nov. near *pseudococci* to the sex pheromone of the vine mealy bug. Entomologie Experimentalis et Applicata 126: 122-130.

Frank S D, Tooker J F. 2020. Opinion: Neonicotinoids pose undocumented threats to food webs. PNAS 117(37): 22609-22613.

Gangwar S K, Srivastava D C, Tewari R K, Singh M R. 2008. Management of *Pyrilla perpusilla* Walker in sugarcane with ecto-parasitoids *Epiricana melanoleuca* Fletcher during epidemics in sub-tropical India. Sugar tech 10(2): 162-165.

Heuskin S, Verheggen F J, Haubruge E, Wathelet J P, Lognay G. 2011. The use of semiochemical slow-release devices in integrated pest management strategies. Biotechnology, Agronomy and Society and Environment 15(3): 459-470.

Himanen S J, Tao L, Blande J D, Holopainen J K. 2017. Volatile organic compounds in integrated pest management of Brassica oilseed crops. In chapter: Integrated management of insect pests on canola and other Brassica oilseed crops, CABI Wallingford, UK. 281-294 pp.

Hinz R, Sulser T B, Huefner R, Mason D'Croz D, Dunston S, Nautiyal S, Ringler C, Schuengel J, Tikhile P, Wimmer F, Schaldach R. 2020. Agricultural development and land use change in India: A scenario analysis of tradeoffs between UN Sustainable Development Goals (SDGs). Earth's Future 8(2):1-19. https://doi.org/10.1029/2019EF001287.

Hodek I, Honek A, van Emden H F. 2012. Ecology and Behaviour of the ladybird beetles (Coccinellidae), Chichester, UK: Wiley-Blackwell Publisher, 600 pp.

Isman M B. 2019. Challenges of pest management in the twenty first century: New tools and strategies to combat old and new foes like. Frontier in Agronomy 1: 2.

Jayanthi P D K, Aurade R M, Kempraj V, Chakravarthy A K, Verghese A. 2015. Glimpses of Semiochemical Research Applications in Indian Horticulture: Present Status and Future Perspectives. In book: New Horizons in Insect Science: Towards Sustainable Pest Management (First Edition), Springer Publisher, India. 239-257 pp.

Kachhawa, D. 2017. Microorganisms as a Biopesticides. Journal of Entomology and Zoology Studies 5(3): 468-473.

Kataria R, Kumar D. 2012. Occurrence and infestation level of sucking pests: Aphids on various host plants in Agricultural fields of Vadodara, Gujarat (India). International Journal of Scientific and Research Publication 2(7): 1-6.

Kataria R, Kumar D. 2020. Reduction of hazardous impact of chemical control from agricultural crops by utilization of different insect biolures. Journal of Entomological and Zoological studies 8(1): 799-804.

Khan S, Yousuf M, Ikram M. 2020. Morphometric based differentiation among *Trichogramma spp*. PLoS ONE 15(8): e0236422.

Koul O. 2011. Microbial Biopesticides: Opportunities and Challenges. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 6(056): 1-26.

Long E Y, Finke D L. 2014. Contribution of predator identity to the suppression of herbivores by a diverse predator assemblage. Environmental Entomology 43: 569 -576.

Malarvannan S, Murali P D, Shanthakumar S P, Prabavathy V R, Nair S. 2010. Laboratory evaluation of the entomopathogenic fungi, *Beauveria bassiana* against the tobacco caterpillar, *Spodoptera litura* Fabricius (Noctuidae: Lepidoptera). Journal of Biopesticides 3 (1 Special Issue): 126 -131.

Mishra R K, Bohra A, Kamaal N, Kumar K, Gandhi K, G K S, Saabale S, S J S N, Sarma B K, Kumar D, Mishra M, Srivastava D K, Singh N P. 2018. Utilization of biopesticides as sustainable solutions for management of pests in legume crops: achievements and prospects. Egyptian Journal of Biological Pest Control 28, Article no. 3.

Mondal P, Kumar A, Tammana. 2021. *Nuclear Polyhedrosis Virus* (NPV): An overview. Bulletin of Environmental Science, Pharmacology and Life Sciences 10(6): 12-19.

Muzemu S, Mvumi B M, Nyirenda S P M, Sileshi G W, Sola P, Chikukura L, Kamanula J F, Belmain S R, Stevenson D C. 2011. Pesticide effects of indigenous plant extracts against Rape aphid and tomato red spider mites. African Crop Science Conference Proceedings 10: 171-173.

Nelson A R L E, Ravichandran K, Antony U. 2019. The impact of the green revolution on indigenous crops of India. Journal of Ethnic Foods 6, Article no. 8.

Nitnavare R B, Bhattacharya J, Singh S, Kour A, Hawkesford M J, Arora N. 2021. Next generation dsRNA- based insect control: Success so far and Challenges. Frontier in Plant Science 12: 673576.

Pardo S G, Jandricic S E, Frank S D. 2015. Ecological interactions affecting the efficacy of *Aphidius colemani* in greengouse crops. Insects 6(2): 538-575.

Poveda J. 2021. *Trichoderma* as biocontrol agent against pests: New uses for a mycoparasite. Biological Control 159: 104634.

Ramasamy S, Sotelo P, Lin M-Y, Hy Heng C, Kang S, Sarika S. 2020. Validation of a bio-based integrated pest management package for the control of major insect pests on Chinese mustard in Cambodia. Crop Protection 135: 104728.

Rao G V R, Rao V R. 2010. Status of IPM in Indian agriculture: A need for better adoption. Indian Journal of Plant Protection 38 (2): 115-121.

Riddick E W. 2017. Identification of conditions for successful aphid control by ladybirds in greenhouses. Insects 8(38): 1-17.

Saini R P, Raman V, Dhandapani G, Malhotra E V, Sreevathsa R, Kumar P A, Sharma T R, Pattanayak D. 2018. Silencing of HaAce1 gene by host-delivered artificial microRNA disrupts growth and development of *Helicoverpa armigera*. PLOS ONE 13(3): e0194150.

Sharma S, Kooner R, Arora R. 2017. Insect pest and crop losses. In Breeding Insect Resistant Crops for Sustainable Agriculture Arora R, Sandhu S, (Editors), Springer Pubisher, Singapore. 45-66 pp.

Shelton A M, Sarwer S H, Hossain M J, Brookes G, Paranjape V. 2020. Impact of Bt Brinjal Cultivation in the Market Value Chain in Five Districts of Bangladesh. Frontiers in Bioengineering and Biotechnology 8: 498.

Shendage N, Sathe T V. 2015. Tachinids as good biocontrol agents of agricultural pests. Biolife 4(1): 79-83.

Singh A, Kataria R, Kumar D. 2012. Repellence property of traditional plant leaf extracts against *Aphis gossypii* Glover and *Phenacoccus solenopsis* Tinsley. African Journal of Agricultural Research 7(11): 1623-1628.

Skula N, Singh E A N A, Kabadwa B C, Sharma R, Kumar J. 2019. Present status and future prospects of bio-agents in agriculture. International Journal of Current Microbiology and Applied Sciences 8 (4): 2138-2153.

Tembo Y, Mkindi A G, Mkenda P A, Mpumi N, Mwanauta R, Stevenson P C, Ndakidemi P A, Belmain S R. 2018. Pesticidal plant extracts improve yield and reduce insect pests on legume crops without harming beneficial arthropods. Frontiers in Plant Science 9: 1425.

Tilman D, Reich P B, Isbell F. 2012. Biodiversity impacts ecosystem productivity as much as resources, disturbance, or herbivory. PNAS 109(26): 10394-10397.

Ukrainsky A S, Orlova-Bienkowskaja M J. 2014. Expansion of *Harmonia axyridis* Pallas (Coleoptera: Coccinellidae) to European Russia and adjacent regions. Biological Invasions 16:1003-1008.

Vikas G, Sharma N, Gavkare O, Khachi B, Singh D K. 2014. Biopesticides- for Future. Journal of Industrial Pollution Control 30(2): 203-205.

Vlassi A, Nesler A, Perazzolli M, Lazazzara V, Büschl C, Parich A, Puopolo G, Schuhmacher R. 2020.Volatile Organic Compounds from *Lysobacter capsici* AZ78 as Potential Candidates for Biological Control of Soilborne Plant Pathogens. Frontiers in Microbiology 11:1748.

Vu V H, Hong S I, Kim K. 2007. Selection of entomopathogenic fungi for aphid control. Journal of Bioscience and Bioengineering 104 (6): 498-505.

(Manuscript Received: June, 2022; Revised: June, 2022;
Accepted: september, 2022; Online Published: October, 2022)
Online First in www.entosocindia.org and indianentomology.org Ref. No. e22036A