Semiochemicals and Their Potential Use in Pest Management in Horticultural Crops

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Abstract Semiochemicals have been exploited in several ways to manage insect pests. These include monitoring and detection, population suppression through mating disruption, mass trapping and attract-and-kill techniques. The male-produced aggregation pheromone is successfully used in food-baited traps for the area-wide integrated management of red palm weevil in date palm, coconut palm and Canary Island palm plantations. Although the pheromones are very effective, environment friendly and economical but their use in the field still remains low. The development of new dispensers and cost-effective formulation will bring about a change in the usage pattern of pheromones. Awareness to farmers and developmental agencies is an important activity for increasing the pheromone intake in field. The future of pheromone technology depends on the smart delivery systems, highly effective pheromones at low doses, modified easy to use traps and cost-effective products.

1 Introduction

Insects mostly rely on chemical communication than the visual communication which plays a vital role in the survival of insects, which enable them to appraise immediate environment through modification of their behaviour. Semiochemicals are organic compounds used by insects to convey specific chemical messages that modify their behaviour or physiology. While the adults utilize various types of chemical signals for their behaviour such as mate finding, host finding, oviposition, aggregation, deterrents, alarm etc., the immature stages utilize rather subtle chemicals mostly for host finding because of their less developed olfactory sensors. Since the first identification of a pheromone over 70 years ago, chemical signals have

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received much attention from scientists in biology, chemistry and applied usage in agriculture/forestry. Many of the findings have come into practical use for monitoring or suppression of insect pests.

Semiochemicals which mediated insect–insect and insect–plant interactions are often used in integrated pest management (IPM) of several insect pests thus considered as complementary to IPM. Crop protection based on semiochemicals has advantages over conventional insecticides, however, is not yet widely used. Semiochemicals are being exploited currently as an important component in management of insect pests of horticultural crops, mainly because of the frustration expressed by a section of farmers who are fed up with the use of repeated application of insecticides, and their associated cost.

2 Semiochemicals and Its Classification

Semiochemical (derived from Greek word *semeon* meaning 'signal') is a generic term used for a chemical that carries a message for purpose of communication. Chemical communication is defined as: the emission of a stimulus by one individual which induces a reaction in another one, the reaction being beneficial to the emitter, to the recipient or both. These semiochemicals based on their function are classified as pheromone, which enables communication within the species and allelochemicals which enables communication between the species. Semiochemicals play an important role in host–parasitoid relationship, which was categorized into three stages: habitat-location, host-location and host-acceptance and oviposition. These semiochemicals included but not limited to aldehydes, alcohols, sulphur-containing compounds, esters, terpenes, alkanes, heterocyclic aromatic compounds, proteins, amino acids, triglycerides and salts. Semiochemicals identified in the habitat-location step were likely to be from the host-plant of the host insect, while in host-location and host-acceptance and oviposition steps; Pheromones are species specific and can be perceived at such a lower dose over long range, even up to 2 km.

2.1 Pheromones

Pheromones are exocrine in origin (and hence named as ectohormone earlier) and elicit a favourable response between the individuals of the same species. There are several types of pheromones, classified based on their functionality.

2.1.1 Aggregation Pheromones

Aggregation pheromones usually are released from the male and attract members of both sexes resulting in mating and aggregation at a food resource. For example, ferruginol (4-methyl-5-nonanol) is an aggregation pheromone of coconut red palm weevil, *Rhynchophorus ferrugineus*.

2.1.2 Alarm Pheromones

These pheromones alert the other members of the same species about the perceptible threats. Some examples are: sesquiterpene (*E*)-β-farnesene (EBF), which is known as the main components of the alarm pheromone of several aphid species.

2.1.3 Oviposition-Deterrent Pheromones

These pheromones discourage females from laying eggs in the same resource of another female. Several fruit flies, e.g. *Rhagoletis pomonella* (Walsh), mark the surface of fruit after oviposition to prevent egg laying by other female flies. Interestingly, females of the parasitic wasp, *Diachasma alloeum* (Muesebeck) which attack the maggots of two species of *Rhagoletis* lay a single egg in a fly maggot, and subsequently deposit a deterrent across the fruit surface by their ovipositor to prevent other females from ovipositing into the marked blueberry, hawthorn or apple fruit.

2.1.4 Home Recognition Pheromones

These are common in social insect colonies. Bee queens produce a scent-mark to enable workers to recognize her colony. Queen recognition pheromones or more simply ‘queen pheromones’ are exocrine gland products released by the queen that usually attract workers to her, eliciting care and protection. The queen benefits from the attention of the workers, and the workers may also use the pheromone signal to gain information about the queen.

2.1.5 Sex Pheromones

Sex pheromones are usually emitted by the female to attract members of the opposite sex (male) for mating. Most of the lepidopteran pheromones are sex pheromones attracting the males. However, male produced sex pheromones are rather rare in insects.

2.1.6 Trail Pheromones

These pheromones guide social insects to distant food sources. Trail pheromones can have both recruitment and orientation effects. 6-*n*-pentyl-2-pyrone was shown to be the main trail pheromone for the myrmicine ant, *Pristomyrmex pungens*.

2.1.7 Recruitment Pheromones

These pheromones induce nest-mates to leave the nest and migrate to a work site or vice versa. The workers of red fire ant, *Solenopsis invicta*, produce pheromone to recruit the fellow workers when the food sources are large.

2.1.8 Royal Pheromones

Recently identified pheromones from subterranean royal termites as a wax-like hydrocarbon composed of only C and H atoms called 'heneicosane'. This pheromone enables workers to recognize patronage (kings and queens), thereby maintaining the strain reproductive division.

2.2 Allelochemicals

Allelochemicals are substances which transmit chemical messages between different species. Based on their function, the allelochemicals are classified as allomones, kairomones, synomones, antimones and apneumones.

2.2.1 Allomones

Allomones are released from one organism that elicits a response in an individual of another species. The response is beneficial to the emitter, e.g. poisonous volatiles and flower volatiles. Granular trichomes which cover plant leaves and stems release herbivore-deterring allomones under stress conditions as a defence process.

2.2.2 Kairomones

Kairomones are emitted by an individual of one species that elicit a favourable response in an individual of another species that is adaptively favourable to the receiving organism but not to the emitting organism. Thus kairomones include plant odours which are used by herbivorous insects to locate their host species, and compounds produced by herbivorous insects which are used by predators and parasitoids to locate or recognize their prey or host. Kairomones used by parasitoids to locate their hosts can be divided into two groups, external to the host, which are long-chain hydrocarbons, ketones of fatty acids, esterified cholesterols or proteins found in either host frass or glue used to attach eggs to a substrate. The internal kairomones represented by amino acids and salts in the haemolymph that have normally been sensed the ovipositors and serve as indicators for suitability of the host for the parasitoid offspring, a kind of maternity care found in many insect species.

Application of L-tryptophan along with tricosane on cotton fields increased the chrysopid populations and thus effectively controlled sucking pests and *Helicoverpa armigera* (Bakthavatsalam & Singh, 1996) and hydrolyzed tryptophan elicited more response than the oxidized tryptophan (Bakthavatsalam & Tandon, 2007). Larvae of *Chrysoperla carnea* responded to the compounds such as tricosane and pentacosane (Bakthavatsalam & Singh, 1999). Scales from lepidopteran moths and their hydrocarbons also elicit behavioural response in the egg parasitoid, *Trichogramma chilonis* (Bakthavatsalam & Tandon, 2006a) and variation between the strains also was observed (Bakthavatsalam & Tandon, 2006b). Larval extracts of *Opisina arenosella* along with the associated cuticular hydrocarbons greatly influence the behaviour of larval parasitoids of *O. arenosella* (Bakthavatsalam et al., 1999).

2.2.3 Synomones

Synomones mediate interactions which are adaptively favourable to both receiving and emitting species; Synomones include volatile compounds produced by plants when attacked by herbivorous insects that attract predators and parasitoids of the attacking herbivores; beneficial to both the releaser and receiver. Examples include scents used by flowers to attract pollinating insects. Moreover, herbivore-induced plant volatiles are considered to be active synomones which recruit natural enemies of insect pests towards the affected plant. Aphd lion (*Chrysoperla carnea*) is known to show positive behavioural response to the cotton plants infested with *H. armigera* (Bakthavatsalam et al., 2000). Also, synomones play an essential role in mate-finding communication. This role relies on the reduction of competition in the olfaction communication channel between closely related species with overlapping pheromone components. This advisable action is important in preventing exhaustion from the time and energy required for orientation towards heterospecifics.

2.2.4 Antimones

Allomones include, for example, both secretions used for defence and attractant compounds used by certain predators to attract their prey; maladaptive for both the releaser and receiver. These substances produced or acquired by an organism that, when encountered by another individual of a different species in the natural environment, activates in the receiving individual a repellent response to the emitting and receiving individuals.

2.2.5 Apneumones

Apneumones are substances emitted by a non-living material that evoke behavioural or physiological responses that are adaptively favourable to the receiving organism but detrimental to a second species found on or in the non-living material. Allelochemicals hexanal and 2-methyl-2-butanol released from rabbit stools attracting sandfly females for oviposition.

3 Isolation, Identification, Synthesis, and Production of Pheromones

Identifying the volatiles that insects can detect in their environment is an important step towards understanding the role of olfaction in modulating insect behaviour. The identification of chemicals involves strong partnership between biologists and chemists. The equipment for extraction and chemical characterization of semiochemicals includes solid-phase microextraction (SPME), gas chromatography-electroantennography (GC-EAD), gas chromatography-mass spectrometry (GC-MS) and nuclear magnetic resonance (NMR). The process of semiochemical identification involves extraction or headspace collection, identification of active compounds, characterization of chemical composition of the identified compound and elucidation of behavioural response of the insect to the active product. If the organ that produces the semiochemical is known, for example, the pheromone gland or the abdominal or thoracic gland of the insect, it can be extracted and identified. Headspace collection is preferred where a charcoal-filtered air is passed over the insect or its organ in an isolated aeration chamber and the odour-laden air is drawn by vacuum for analysis using GC-EAD or GC-MS using suitable capillary columns. Electroantennogram (EAG) technique measures the difference in measurable voltage between the tip and base of the insect antenna when exposed to odours of biological significance. The electroantennogram was improved through time and the insect antenna has been used as a detector (EAD) for a capillary-column gas chromatography, which is coupled with the flame ionization detector (FID) that is sensitive to all organic molecules. The GC-EAD is gas chromatography coupled with electroantennographic detection of compounds present in complex mixtures. It is widely used to discover and identify semiochemicals, more specifically insect pheromones. The FID output can be used to confirm the presence, identity and quantity of compounds present in the extracts while the antennal (EAD) output indicates the olfactory sensitivity to eluting compounds and provides a relative measure of the intensity of olfactory stimulation. Identifications can be confirmed by re-analysing the extract with a coupled GC-MS spectrometer using the same column and GC operating parameters as used in the GC-EAD analysis.

Behavioural assay techniques such as olfactometer and wind tunnel are employed to test the behavioural activity of the insects to the volatiles synthesized after identification. Synthesis has also been essential for the development of pheromone-based control methods of many lepidopteran insect pests. Common lepidopteran pheromone constituents are long-chain saturated or unsaturated alcohols and their derivatives (acetates and aldehydes). Efficient and selective syntheses of such compounds have been part of the development of pheromone-based control methods.

The structure of pheromones especially the presence of double bonds, isomers and functional groups such as aldehydes, ketones also are very important for synthesis and are identified using NMR spectroscopy. The blends of two or more chemicals and their ratio define the specificity of the pheromones.

Some of the insects for which semiochemicals are available and the future scope is given in Table 1.

4 Semiochemical-Based Pest Control Strategies

Insect pheromones were discovered in 1959 with the discovery of *Bombykol*, sex pheromone for *Bombyx mori* and since then thousands have been characterized. Synthetic pheromones have become an important component of integrated pest management (IPM). Pheromones are applied for controlling insect pests in two different ways: indirect control and direct control. Indirect control involves monitoring for quarantine and spray timing strategy, whereas direct control involves mass trapping and area-wide mating disruption applications. Additionally, pheromone traps can explore information about the population such as sex ratio, mating status of the females in a population which is a tool to know the population phase, help in understanding the genetic diversity of some groups (such as Cerambycids) of insect pests. Pheromone traps are used for different purposes in pest management strategies. For example, pheromone-baited traps are used as attracticide or mating disruption techniques to prevent males from reproducing. Thus the control strategies of insects based on semiochemicals include monitoring, mass trapping, lure and kill (attract-annihilate), mating disruption and push–pull strategy (stimulo-deterrent diversion).

4.1 Monitoring

Pheromone traps provide an easy, efficient and extremely sensitive way to detect presence of different insect species in the fields. The pheromone traps such as sleeve traps or box traps along with the lures are available for monitoring the insect species. The insects trapped in the monitoring traps give information on the appearance of the pests and also the population levels of the pests in some cases. Several studies have predicted the intensity of the pest population as well as the predicted onset of the insect pest based on trap catches. Generally 1–3 traps/ha is used for monitoring

Table 1 List of semiochemicals available for Horticultural crop pests

Crop	Insect pest	Status of semiochemicals		
		Global	India	Future scope
Mango	Fruit flies—*Bactrocera* spp.	PP	PP	K, +
	Stone weevil—*Sternochetus mangiferae*	–	–	K, AgP, +
	Hopper—*Ideoscopus* spp.	–	–	K,
	Gall midges—*Procontarinia* spp. *Erosymia indica*	–	–	K, SP
	Psyllid—*Apsylla cistellata*	–	–	K
	Leaf webbers—*Orthaga* spp.	–	–	K, SP
	Leaf miner—*Acrocercops syngramma*	–	–	K, SP
	Leaf eating weevil—*Deporaus marginatus*	–	–	K, SP/AgP
	Shoot borer—*Chlumetia transversa*	–	–	K, SP
	Stem borer—*Batocera rufomaculata*	–	–	K, SP/AgP
Banana	Rhizome weevil—*Cosmopolites sordidus*	SP	SP	K, SP/AgP
	Stem borer—*Odoiporus longicollis*	–	–	K, SP, AgP, +
	Fruit scarring beetle—*Colaspis hypochlora*	–	–	K, SP/AgP
Citrus	Citrus leaf miner—*Phyllocnistis citrella*	SP	–	K, SP,+
	Citrus psyllid—*Diaphorina citri*	–	–	K
	Whiteflies—*Aleurocanthus citriperdus*	–	–	K, SP
	Lemon butterflies—*Papilio* spp.	–	–	K, SP
	Black aphids—*Toxoptera* spp.	–	–	K, AlP
	Blackfly—*Aleurocanthus woglumi*	–	–	K, AlP
	Bark eating caterpillars—*Indarbela quadrinotata*	–	–	K, SP
	Stem boring beetles—*Chelidonium* spp.			K, SP/AgP
	Fruit sucking moths—*Eudocima* spp.			K, SP
Guava	Fruit flies—*Bactrocera* spp.	PP	PP	K, SP, +
Grapes	Flea beetles—*Scelodonta strigicollis*	–	–	K
	Berry webber—*Adoxophyes privatana*	SP	–	SP
	Shot hole borer—*Xyleborus* spp.	–	–	K, AgP
Sapota	Chikoo moth—*Nephopteryx eugraphella*	–	–	SP
	Leaf miner—*Acrocercops gemoniella*	–	–	SP
	Bud borers—*Anarsia species*	–	–	SP
	Seed borer—*Trymalitis margarias*	–	–	SP
Pomegranate	Pomegranate butterfly—*Deudorix isocrates*	–	–	K, SP

(continued)

Table 1 (continued)

Crop	Insect pest	Status of semiochemicals		
		Global	India	Future scope
Ber	Fruit fly—*Carpomyia vesuviana*	–	–	K, SP, PP
	Fruit borer—*Meridarchis scyrodes*	–	–	SP
Litchi	Litchi stink bug—*Tessaratoma papillosa*	–	–	K, SP/AgP
Temperate fruits	Codling moth—*Cydia pomonella*	SP	SP	K, SP, +
	Stem borer—*Apriona cinera*	–	–	K, AgP, SP+
	Tent caterpillar—*Malacosoma indica*	–	–	SP
	Leopard moths—*Zeuzera* spp.	–	–	SP
	Leaf roller—*Archips termias*	P	–	SP
	Peach twig borer—*Anarsia lineatella*	P	–	SP
	Walnut weevil—*Alcidodes porrectirostris*	–	–	K, SP, +
Vegetables				
Tomato	Fruit borer—*Helicoverpa armigera*	SP	SP	K
	Tobacco caterpillar—*Spodoptera litura*	SP	SP	K
	Serpentine leaf miner—*Liriomyza trifolii*	–	–	SP
	Whitefly—*Bemisia tabaci*	–	–	SP, HD
Brinjal	Fruit and shoot borer—*Leucinodes orbonalis*	SP	SP	K, SP, +
	Ash weevil—*Myllocerus* spp.	–	–	SP, K, +
	Epilachna beetle—*Epilachna vigintioctopunctata*	–	–	K, SP, +
	Mealy bug—*Coccidohystrix insolita*	–	–	K, SP, +
	Gall midge—*Asphondylia* sp.	–	–	K, SP, +
Chilli/Capsicum	Thrips—*Scirtothrips dorsalis*	–	–	A, HD
	Green peach aphid—*Myzus persicae*	A, AlP	–	A, AlP, +
	Gall midge—*Asphondylia capsici*	–	–	K, SP, +
Okra	Leafhopper—*Amrasca biguttula*	–	–	K, Agp
	Shoot and fruit borer—*Earias* spp.	SP	–	SP
	Aphid—*Aphis gossypii*	SP	–	SP, HD
	Red cotton bug—*Dysdercus cingulatus*	–	–	K, SP, +
Cruciferous vegetables	Diamondback moth—*Plutella xylostella*	SP, K	SP	SP, K, +
	Leaf webber—C*rocidolomia binotalis*	SP	–	SP, K, +
	Stem borer—*Hellula undalis*	SP	–	SP, K, +
	Cabbage butterfly—*Pieris brassicae*	A	–	K, SP, +
	Aphids—*Brevicoryne brassicae and Lipaphis erysimi*	–	–	K, AlP, HD, +
Leguminous vegetables	Stem fly—*Ophiomiia phaseoli*	–	–	K, SP, +

(continued)

Table 1 (continued)

Crop	Insect pest	Status of semiochemicals		
		Global	India	Future scope
	Pod borer—*Lampedis boeticus*	–	–	K, SP, +
	Aphids—*Aphis craccivora* and *Acyrthosiphon pisum*	–	–	K, SP, HD, +
	Bruchids—*Callosobruchus chinensis*	A, SP	–	K, SP, +
Cucurbits	Fruit flies—*Bactrocera cucurbitae*	MA	MA	K, SP, +
	Red pumpkin beetle—*Aulacophora foveicollis*	–	–	K, SP, +
	Leaf eating caterpillar—*Diaphania indica*	SP		SP
Onion/Garlic	Thrips—*Thrips tabaci Lindeman*	K, A	–	K, HD, +
Tuber crops				
Potato	Tuber moth—*Phthorimaea operculella*	P	–	SP, K, +
	White grubs—*Holotrichia* sp.	A	A	K, SP, +
	Green leaf hopper—*Empoasca kerri*	–	–	K, HD, +
	Green peach aphid—*M. persicae*	A, SP	–	A, SP, HD, +
Sweet potato	Sweet potato weevil—*Cylas formicarius*	K, SP	K, SP	K, SP, +
Coconut	Rhinoceros beetle—*Oryctes rhinoceros*	AgP, A	AgP	K, SP, +
	Red palm weevil—*Rhynchophorus ferrugineus*	AgP, A	AgP	K, AgP, +
	Black headed caterpillar—*Opisina arenosella*	SP	SP	K, +
Cashew	Stem/root borer—*Plocaederus ferrugineus*	–	–	K, SP, +
	Tea mosquito bug—*Helopeltis antonii*	–	–	K, SP/AgP
Coffee	White stem borer—*Xylotrechus quadripes*	A, AgP, CP, CuH	AgP	K, AgP, SP, +
	Coffee berry borer—*Hypothenemus hampei*	A	A	K, SP, +
	Shot hole borer—*Xylosandrus compactus*	A	–	K, SP, AgP, +
Spice crops				
Areca nut	Root grub—*Leucopholis burmeisteri*	SP	–	K, AgP, SP, +
	Inflorescence caterpillar—*Tirathaba mundella*	–	–	K, P, +
Ginger/Turmeric	Shoot borer—*Conogethes punctiferalis*	SP	SP	K, SP, +
	Leaf roller—*Udaspes folus*	–	–	SP
	Thrips—*Panchaetothrips indicus*	–	–	A, HD
	Cigarette beetle—*Lasioderma serricorne*	Al, MaP	–	Al, MaP, SP, +
Cardamom	Shoot borer—*Conogethes punctiferalis*	SP	SP	K, SP, +

(continued)

Table 1 (continued)

Crop	Insect pest	Status of semiochemicals		
		Global	India	Future scope
	Whitefly—*Dialeurodes cardamomi*	–	–	A, Al, HD, +
	Thrips—*Sciothrips cardamomi*	–	–	A, Al, HD, +
Pepper	Pollu beetle—*Longitarsus nigripennis*	SP	–	SP, K, +

A Attractant, *AgP* Aggregation pheromone, *Al* Allomone, *AlP* Alarm pheromone, *CP* Contact pheromone, *CuH* Cuticular hydrocarbons, *HD* Host plant defence, *K* Kairomone, *MaP* Marking pheromone, *PP* Parapheromone, *PgS* Phagostimulant, *SP* Sex pheromone, **+** Mixtures

insect species. Pheromone traps for important insect species such as *H. armigera*, *Plutella xylostella*, *Pectinophora gossypiella*, *L. orbonalis*, *Scirpophaga incertulas*, and *Chilo* spp. are commercially available for monitoring the insects in varied crop systems.

Pheromones especially parapheromones such as methyl eugenol, cuelure and trimedlure have been extensively used for the quarantine monitoring of fruit flies in several countries. These traps are deployed in different ports of entry and other important places such as airports and seaports where commodities or plants are imported. Alert is given to the concerned officials when flies were caught in the traps and subsequent measures were undertaken to contain the pest becoming a serious pest.

In countries where insects are introduced for the management of weeds, pheromone traps have been effectively used to document the establishment and spread of insects to the newer areas. *Xubida infusella,* a weed killer on *Eichhornia crassipes, Agapeta zoegana* on *Centaurea maculosa* and *Carmenta mimosa* on *Mimosa pigra* are few examples where pheromones are used.

4.2 Mass Trapping

Pheromones are directly used for the management of insects by suppressing the populations of insects. The traps are deployed in sufficient numbers (10–40 per ha) so that the adults are trapped. This technique is more effective in coleopteran insects where aggregation pheromones were used to trap both the sexes of the insect and thus eliminating their populations. Synthetic pheromones have also been used in IPM to mass trap insects such as coffee stem borer (*Xylotrechus quadripes*) and red palm weevil (*R. ferrugineus*) on coconut and areca nut in order to decimate large populations of insects from the breeding and feeding areas. Mass trapping is very effective with insects having relatively low population, live a long time before egg-laying and lay small number of eggs, and have lesser range of host plants and may not be effective for polyphagous insect pests. In some lepidopteran insects such as fall army worm (*Spodoptera frugiperda*) deployment of sleeve traps with dispensers @ 15 per ac gave sufficient reduction in egg laying and subsequent reduction in populations.

4.3 Attract and Kill System

Attract-and-kill system is a more recent approach for pest management, and the purpose of this system is to use a synthetic pheromone to bring a target insect in contact with an insecticide. Attract-and-kill systems are powerful control strategies because target male insects are removed from the ecosystem. Pheromones can be added to traps in order to attract males searching for a female for mating. Specifically, synthetic lures are placed inside of specially designed traps. The technique as the name implies simply use an attractant or semiochemical to lure an insect to a point source that contains a killing agent (insecticide, pathogen or sterilant). A trap can be a simple roof structure with a sticky bottom to entrap insects, or a roof over a funnel with a container for retaining insects that fall into a funnel. The technique leads to the reduction of the insect population by killing the target insect or reducing its fitness and fecundity or disabling it by causing disease. Attract-and-kill is a tactic used for trapping and simultaneously killing the captured pests. This strategy has been applied to insect pests of both field crops and stored products.

4.4 Mating Disruption

Mating disruption is an effective method to reduce the populations of insects, mostly moths which utilize sex pheromones. The quantity pheromones used to cause mating disruption is huge, ranges from 24 to 150 g per ha per crop. Synthetic pheromones have been used in IPM to disrupt mating in populations of insects. Mating disruption is a strategy which uses species-specific sex pheromones that affect mating behaviour by releasing huge amounts of synthetic pheromones into the atmosphere. This application has been most effectively used with agriculturally relevant moth pests. Synthetic pheromone product is dispersed into crops creating plumes that can attract males away from females that are waiting to mate or prevent males from locating a female with which to mate. This causes reductions in mating and thus reduces the population density of the pests. In some cases, the effect has been so great that the pests have been locally eradicated. It manipulates insect behaviour in such a way that leads to population reduction. The environment where specific insect pest needs to be controlled is saturated with synthetic sex pheromones so that the abilities of males to locate the natural pheromone plume emitted by females are disrupted. Insect females have a critical time to mate and reproduce and any delay of mating may affect their fitness and their abilities to select the suitable sites for oviposition. Delay in females mating may reduce their fecundity by approximately 50%. The mating system of some insects involves the transfer of certain peptides that trigger the egg laying behaviour in the females. El Shafie and Faleiro (2017) described four mechanisms were proposed to explain how mating disruption occurs, and these are:

(a) **Competitive attraction or false trail following:** This happens when males respond to synthetic pheromone plumes produced by semiochemical dispenser rather than the natural plume emitted by the calling female. This mechanism is density-dependent and decrease in efficiency as the population of pest increases.
(b) **Camouflage:** This mechanism requires complete saturation of the environment with the synthetic pheromone. In this case, the male cannot locate the positions of the females and it is density-independent.
(c) **Desensitization:** Adaptation of the male olfactory receptor system or habituation of the central nervous system may occur due to the overexposure to synthetic pheromone.
(d) **Sensory imbalance:** Adaptation of the male olfactory receptor system or habituation of the central nervous system may occur due to the overexposure to synthetic pheromone. For mating disruption the quantity of pheromones used was very high which indirectly increases the cost of application. This has facilitated to the development of various dispensers such as 'checkmate cmxl, isomate ctt, isomate c-plus, cidetrak cm, pb-rope, SPLAT' etc. which can be easily used with cost effectiveness. Recent advancement in the synthesis of pheromone using cold press process and edible gum based dispensers (SPLAT) has shown promise for the use of mating disruption technology in the management of *L. orbonalis* and *Pectinophora gossypiella.* Male annihilation technique is another type of mating disruption whether the male population is decimated using the pheromone traps. Fruit fly management is widely achieved using the parapheromones such as methyl eugenol, cuelure and trimedlure for *Bactrocera dorsalis*, *Bactrocera cucurbitae* and *Ceratatis capitata*, respectively. A bisexual attractant in combination with parapheromones gave excellent control of fruit flies in mango, guava, orange, cucurbits and tomato.

4.5 Push–Pull Strategy

Push–pull strategy represents an important strategy and it also called 'stimulo-deterrent diversion tactic'. It is a combination of deterred or repellent from the crops (push strategy) and attractive stimuli by lures (pull strategy), which control the insect pests by trapping or killing tactics. This strategy obviously requires knowledge of insect biology, chemical ecology and the interactions between host plants and natural enemies. The potential use of aphid alarm pheromone as a direct control mechanism has been pheromones and heterospecific synomones. Heterospecific synomones are adaptive for insects either to avoid aggregation and orientation to the wrong species or to be directed to a resource. Efforts have also been made to incorporate alarm pheromones as repellents in push–pull strategies, in order to make the protected resource unattractive to the pest. Also, orientation disruption of bark beetles away from their host trees is combined with attractive semiochemical deployment in a ‘push–pull’ tactic.

4.6 Other Strategies Using Semiochemicals

Other semiochemicals which are used to facilitate biological control of insect pests include kairomones and/or synomones. These semiochemicals are used as synthetic bait or as an attractant by insects to find prey, hosts or food. These compounds catch a wide spectrum of species that use similar resources and are frequently less attractive than pheromones. Furthermore, utilization of host-plant volatiles is being studied as new active compounds for termite management. Subsequently, a combination of different semiochemicals recently was used for management of some important insect pests.

5 Trapping Technology

Pheromone traps can attract the insect pests within one-quarter mile from the trap site.

5.1 Type of Traps

Traps are designed to capture and kill the target insect and these traps are designed based on the behaviour of the insects. Most common trap is the sticky trap and colour plays an important role in trapping. Yellow, blue and white traps are effectively used for trapping insects such as fruit flies, thrips, hoppers and small lepidopterans. These sticky traps are also used in the delta format with the advantage that these traps are not destroyed by weather factors such as temperature and rainfall. However, one major disadvantage in using the sticky/delta traps is that several non-target insects including pollinators and predators and parasitoids are also trapped and killed. Sleeve traps are used to trap the moths which cannot escape from the traps. Sometimes for small lepidopteran and fruit flies top pan trap is used for trapping the adults. A plastic box (750 mL capacity) with two holes on the one-third of the top portion along with the wooden dispensers effectively caught good number of fruit flies.

For beetles such as *Rhynchophorus ferrugineus* bucket traps are used with gunny bag covered on the top surface to allow the adults to alight and enter the trap.

A sticky trap with pheromone lures used for trapping *Tuta absoluta*

Plastic box modified for trapping mango fruit fly, *Bactrocera dorsalis* along with wooden dispenser

***Bactrocera dorsalis* caught in the traps**

Sleeve trap for trapping lepidopteran insects.

Fruit flies caught in yellow delta traps using attractant with good proportion of females

Top Pan trap for trapping small bisexual lepidopterans and fruit flies

Bucket trap used for trapping the beetles or weevils.

Traps need to be installed at the canopy levels for the annual or seasonal crops and for perennial trees crops to be installed at least 3–4 feet height. Some of the traps need regular servicing, for example. Traps for *R. ferrugineus* need to be serviced by removing the dead adults and replacing the baits along with the poison at weekly intervals. The number of traps varies with the target species as well as the application. In case of monitoring the number of traps used is very less, for example, in case of *H. armigera* the number is very less (1–2 traps/ha) and for *R. ferrugineus* 1 trap/2 ha. However, for mass trapping the number will very high, for example *Spodoptera frugiperda*, 15 traps/ac and for coffee stem borer, *X. quadripes* 10 traps/ac are used. Traps also to be installed during the expected activity of the target pest.

Dispensers: The choice of dispenser (solid matrix, formulation, reservoir, puffer) will mainly depend on the needs of the crop farmers, taking into account the labour and the manpower costs to implement IPM strategies. Environment protection can also be determinative in the dispenser selection. Biodegradable matrix, environmentally safe, could be preferred as slow release device material for semiochemical delivery. The best way to estimate diffusion efficiency consists in regularly measuring the residual semiochemical quantity and/or determining release rate from field-aged dispensers. This approach, generally less time consuming, gives a direct indication of the dispenser release effectiveness and the moment to replace pheromone delivery system on field. Rubber septa, vials, wooden blocks, bottle dispensers, PB rope, SPLAT are some of the dispensers used. Biogradable dispensers have been developed for almost all the insects with good results.

6 Applications of Semiochemicals

6.1 Fruitflies

Volatile fruit odours have been used successfully as attractants for the apple maggot fly *R. pomonella*, Mediterranean fruit fly *Ceratitis capitata,* the Mexican fruit fly *Anastrepha ludens* and Caribbean fruit fly *Anastrepha suspensa*. Male annihilation technique (MAT) is largely confined to tephritid fruit flies in mango as well as in other crops, viz. guava, citrus in India. Visual and chemical cues play an important role in the host-finding behaviour of fruit fly *Dacus dorsalis*, since, the host plant is the focal point for the ecological behaviour of fruit flies involving host seeking, adult feeding, mating behaviour, oviposition and egg development, these functions are strongly modulated by chemical cues. Erecting of methyl eugenol wooden block traps during fruiting period @ 20 traps/ha brings down the male population in mango (Verghse et al., 2014). Studies on the attract-and-kill tactic have been either for long-term pest management; or they have been used for eradication of invasive species tephritid fruit flies. A male parapheromone with higher attraction than the methyl eugenol was developed and this parapheromone along with a bisexual attractant (which attracts males and females) in sawdust kept in yellow delta traps deployed @ 5 traps per acre in mango, guava and Coorg mandarin oranges has greatly reduced the incidence by *B. dorsalis* (Bakthavatsalam et al., 2017a, 2017b, 2017c). Gamma octalone was identified as the ovipositional stimulant for the *B. dorsalis* (Pagadala Damodaram et al., 2014). Cuelure is a parapheromone which attracts the males of *B. cucurbitae*. Commercially this cuelure impregnated in the plywoods has been recommended @ 20 per acre on cucurbitaceous vegetable crops (Verghese). A new technology was developed wherein a formulation of cuelure with higher attraction than the cuelure along with zero alcohol based impregnation technique was developed and commercialized (patent applied). This cuelure technology along with the bi sexual attractant has given excellent control of *B. cucurbitae* in cucurbit crops and tomato (Verghese et al., 2017a).

6.2 Longhorned Beetles

There is a growing body of evidence that hydrocarbons within the epicuticular wax layer of females serve as contact pheromones, and play important roles in the mating systems of longhorned beetles. Further, long range mate location mediated by pheromones has been documented in several sub families of Cerambycidae including Lamiinae, through both male-produced (Reddy et al., 2005) as well as female-produced sex pheromones (Ray et al., 2011). Both sexes are reported to get attracted to host kairomones, male-produced pheromones, host kairomones + male produced aggregation pheromones or host/bark kairomones + male produced aggregation pheromones. In a few species, females are attracted to male-produced sex pheromones or a combination of host kairomones + male produced sex pheromones. The role of semiochemicals in mate location in majority of cerambycids apparently appears quite complex involving possible role of male and female pheromones and kairomones. A detailed multi-faceted behavioural approach to understand the mate/host location perhaps will provide a needed tool for pest management, survey and detection and control for this important polyphagous cerambycid. Attractiveness of ammonium carbonate as a general olfactory cue combined with a five-component apple volatile mixture has been used in a red attracticidal sphere system for controlling the apple maggot fly (Morrison et al., 2016). *B. rufomaculata* is a serious trunk borer of mango and other crops. The volatiles especially pheromones for this pest remains to be identified. However, repellent formulations have been developed at Indian Institute of Horticultural Research, India which has shown good results in avoiding infestation for longer periods. The senior author along with other scientists has developed a plant-based repellent formulation applied during the pre-monsoon and post-monsoon seasons recorded least infestation, saving the trees (Verghese et al., 2017b).

6.3 Grape Root Borer Moth

Attract-and-kill system has been commonly used in killing the grape root borer moth and requires less insecticide than standard insecticide.

6.4 *Mango Fruit Borer (*Deanolis albizonalis*)*

An effective pheromone lure has been identified by Hortresearch in New Zealand that trapped hundreds of male moths and was significantly more attractive than virgin female moths, catching six times more moths than caged virgin females suggesting the possibility of routine trapping of male moths for monitoring as well as for mating disruption. Initial testing suggested the lure was effective for at least 3 weeks in the field under tropical conditions and further work needs to be done on trap type, lure matrices (instead of rubber septa), mating behaviour, dispersal and lure attractancy range (Gibb et al., 2007).

6.5 *Mango Leaf Webber (*Orthaga exvinacea*)*

Recent studies clearly proved that *O. exvinacea* tags along with conspecifics through multiple ovipositions by several conspecific gravid females into the same web and/or nearby web. Further experiments to find out the cues aiding the gravid female to oviposit within the same web or near the already existing web and female based sex pheromone definitely help in luring both sexes into traps. Similar attempts to locate female-based sex pheromones may yield positive results in another lepidopteran, early shoot borer, *C. transversa* (Kamala Jayanthi et al., 2015).

6.6 *Apple the Codling Moth*

The olfactory system of insects is very sensitive, and limited amounts of semiochemicals are needed for control. This is demonstrated by the current application of pheromones for control (mating disruption by confusion strategy) of codling moth (*Cydia pomonella*) in apple orchards. Successful synthesis of codlemone, the codling moth female sex pheromone blend has led to behaviour-based monitoring and management of codling moth infestations in apple (Lo et al., 2013). Mass trapping has also been used successfully against the codling moth, a serious pest of apples and pears.

6.7 *Banana Weevils*

Semiochemical-based trapping in banana weevil management has potential either in mass trapping or as part of IPM programs. Banana rhizome weevil, *Cosmopolites sordidus*, a commercial male aggregation pheromone—Sordidin was identified by Budenberg et al. (1993) and is popular. Monitor the weevil activity in a garden by keeping longitudinal split banana pseudostem traps at 10–15/ha. Once weevil is attracted to the laid traps, keep the longitudinal split banana traps at 100/ha with biocontrol agents. Pheromone attracts both male and female adults. Pheromone traps at 5 traps/ha are to be installed (6 months lure life span). The position of traps should be changed once in a month. Bucket traps are used for monitoring and for mass trapping of adults (Padmanaban & Lakshmi Balaji, 2010). In case of pseudostem borer, *O. longicollis*, the weevils were already known to get attracted to cut stems of host plant and conspecifics. Baiting with male aggregation pheromone (2-methyl-4-heptanol) of *O. longicollis* in conjunction with host plant extract in funnel traps attracted significantly more weevils than traps baited with either pheromone or host plant extract alone (Palanichamy & Ya-Ping, 2011). Further, evidence for a female-produced sex pheromone which is attractive to male weevils was also reported (Ravi & Palaniswami, 2002). Pseudostem weevil activity in a garden can be monitored by laying banana longitudinal split traps and if the weevils attracted to the traps, control measures have to be taken up immediately. A repellent formulation was developed which gave excellent protection of banana plants for 4–6 months from *O. longicollis*.

6.8 Fruit Borer—Deudorix isocrates

Existence of strong female-based sex pheromone communication system in pomegranate fruit borer *D. isocrates* was identified by Indian Institute of Chemical Technology (IICT) in collaboration with Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri. Three sex pheromone components have been identified and synthesized successfully in the lab and confirmed their bioactivity by GCEAD (Seema, 2009).

6.9 Pear Psylla: Cacopsylla pyricola

Optimizing a *sex* pheromone-based method of monitoring may help to attract pear psylla *C. pyricola* (Guédot et al., 2009). Similarly, a psyllid repellent that was discovered by scientists exploring why citrus trees planted near guava trees had fewer citrus psyllids revealed that the compound dimethyl disulphide (DMSD), identified in volatiles emitted by the guava trees was found in laboratory tests to be highly repellent to citrus psyllid. Recent trials have shown that the potato psyllid is also repelled by the compound.

6.10 *Lesser Date Moth*—**Batrachedra amydraula** *and Red Palm Weevil* **R. ferrugineus**

The use of pheromone traps and sticky trap is a best way to control of the date moth *B. amydraula*. Management of red palm weevil *R. ferrugineus* includes careful monitoring, trapping, and removal of infested palms. Traps can be baited with an aggregation pheromone a 9:1 blend of 4-Methyl-5-Nonanol and 4-Methyl-5-Nonanon plus fresh date fruit. Prevention of the infestation is essential, and the practice of good cultural techniques will protect the date plantation from infestation by weevils (Haldhar et al., 2015). Monitoring strategy was used to evaluate the abundance of on the lesser date moth *B. amydraula* Meyrick .

6.11 *Shoot and Fruit Borer* **Leucinodes orbonalis**

(E)-11 hexadecenyl acetate + (E)-11-hexadecen-1-o1 (100:1) (popular as Leucilure for brinjal fruit and shoot borer, *L. orbonalis*); Installation of sex pheromone traps @12/ha at canopy level or slight above the canopy to monitor and mass trap the adult moth population of brinjal shoot and fruit borer *L. orbonalis.* Best control of this pest was achieved with the SPLAT formulation of pheromone in India.

6.12 *Tomato Pinworm* **Tuta absoluta**

In case of pheromone trap catches more than ten moths per trap per week, control treatments are recommended to be carried out by combining bio-rational insecticides with synthetic chemical insecticides. In low population densities, mass trapping of the pest with pheromone baited water traps has also proved to be an effective control measure. An average of 30–40 pheromone baited water traps should be placed per hectare of water. In Egypt, many researchers used monitoring strategy for estimating population fluctuations of different insect pests, such as *T. absoluta* (Meyrick) (Abd El-Ghany et al., 2016). A nanodispenser was developed at NBAIR which is having high efficiency and field persistence even at low doses. A commercial SPLAT formulation was developed by an Indian based commercial manufacturer for mating disruption with excellent results.

6.13 *Fruit Borer* **Helicoverpa armigera**

(Z) 11 hexadecanal + (Z) hexadecanal (97:3) (popular as Helilure for *H. armigera*); Installation of sex pheromone traps @ 5 in pearl millet (Juneja et al., 2015) or 12/ha will help to monitor and mass trap the adult moth population. Unlike the popular belief that the traps placed on the canopy level will record more catches, traps placed at 6 feet height recorded more adults in chickpea plots (Ujjan et al., 2019). Pheromone lures are commercially available and fitting well in to the current IPM programs. Mass trapping with 50 traps/ha in tomato plots reduced the egg and larval and reduced incidence (Shah et al., 2017). Minimum temperature and relative humidity was found to influence pheromone catches significantly (Basavaraj et al., 2013. Pheromone traps were also used for screening of susceptible and resistant lines of chickpea (Bouslama et al., 2019). Funnel traps baited with synthetic floral odours of African marigold, *Tagetes erecta* and sweet pea, *Lathyrus odoratus* caught significantly more *H. armigera* (Bruce & Cork, 2001). The marigold blend contained benzaldehyde, (+)-linalool, phenylacetaldehyde and (S)-(–)-limonene and the sweet pea blend (–)-linalool, phenylacetaldehyde, benzyl alcohol and diacetone (4-hydroxy-4-methyl-2-pentanone) in natural ratio. Although the target specificity and level of attraction obtained with floral traps was too low for mass trapping, the floral cues could possibly be used for monitoring female *H. armigera* populations in their integrated control. Attempts to use different types of traps were made; however, delta traps were found to be detrimental to the non-target insets (Fite et al., 2020).

6.14 Leaf Eating Caterpillar

Spodoptera litura (Z, E), 9,11 tetradecanyl acetate + (Z, E) 9,12-dienyl acetate (19:1) (popular as Spodolure for *S. litura*) are commercially available and fitting well in to the current IPM programs.

6.15 Diamondback Moth

Plutella xylostella(Z)-hexadecanal-11-enal + (Z)-exzadec-11-enyl acetate (popular as Nomate-DBM, Checkmate for diamondback moth-DBM, *P. xylostella*) are commercially available and fitting well in to the current IPM programs. In field experiments, significantly more diamondback moths were captured in traps baited with synthetic sex pheromone with either (*Z*)-3-hexenyl acetate alone or a blend of (*Z*)-3-hexenyl acetate, (*Z*)-3-hexen-1-ol and (*E*)-2-hexenal compared with sex pheromone alone and other blend mixtures demonstrating that green leaf volatiles (GLVs) could be used to enhance the attraction of *P. xylostella* males to sex pheromone-baited traps (Li et al., 2012).

6.16 *Whitefly* Bemisia tabaci

Installation of yellow sticky trap @ 15 traps/ha at canopy level helps to monitor and mass trap flying adult flies.

6.17 *Potato Tuber Moth* Phthorimaea operculella

The existing sex pheromones (mixtures of *trans*-4, *cis* 7-tridecadienil-1-ol-acetate and trans-4, *cis*7, *cis*-10 tridecatrienil-1-ol-acetate compounds in a ratio of 1:1.5) are being used as an ideal tools for monitoring moth flight activity of *P. operculella* (Raman, 1988).

6.18 *Sweet Potato Weevil* Cylas formicarius

Management of SPW took a tremendous path after the discovery of the sex pheromone, (Z)-3-dodecen-1-ol (E)-2-butenoate by Heath et al. (1986) and thus become an important precise component in the monitoring, control and subsequent eradication programs in different parts of sweet potato growing countries globally (Rajasekhara Rao et al., 2010). Isolation of boehmeryl acetate (a pentacyclic triterpenoid) that serves as a potent kairomone for attracting both sexes lead to pheromone–kairomone combinations that contributed to significant reduction in weevil populations and subsequent tuber damage (Palaniswami et al., 2000). A new SPW pheromone formulation, a combination of visual stimulation, pheromone and insecticide exhibited a synergistic response among weevils thereby lowering the cost of application (Yasuda et al., 2004).

6.19 *Coconut Black Headed Caterpillar* Opisina arenosella

Volatile compounds from undamaged, larval damage coconut leaflets, larval frass and larval body wash were identified as acetophenone, limonene, linalool, hexanal hexanol and nonanal. Females were more attracted to acetophenone, linalool and limonene for oviposition. Both male and female evoked higher response to linalool acetophenone and combination of female sex pheromone to plant volatile. Behavioural assay revealed that combination of linalool: sex pheromone (1:1) and acetophenone: sex pheromone (2:1) caused higher response in males as compared to use of sex pheromone alone. Use of sex pheromone in tandem with host related volatiles is suited for management of *O. arenosella*. Female sex pheromone of black headed caterpillar, *O. arenosella* was also identified and developed in India by Pest

Control India (PCI) with detailed studies on dispensers, dosage and traps to suit field conditions.

6.20 *Coconut Rhinoceros Beetle* Oryctes rhinoceros

Discovery of ethyl 4-methyloctanoate (E4-MO), as the male-produced aggregation pheromone and its commercial synthesis led to E4-MO (=rhinolure). Synthetic aggregating pheromone, ethyl 4-methyloctanoate was used in bucket and PVC trap for monitoring and mass trapping of CRB. Ethyl 4-methyloctanoate (E4-MO) and Ethyl 4-methyloctanoate were synthesized by ChemTica and marketed as Oryctalure in India. Buckets of 18 litre capacity with black painted metal vanes were used as trap. The pheromone sachet was hung on the diamond shaped hole made in the vane. The trap was hung on a pole at 3–4 cm above the ground level. Coconut petioles were placed in the bucket trap for better attraction. A nanomatrix has been developed at CPCRI for the delivery of rhinoceros beetle pheromone and it works with lower load of chemistry and has longer field efficacy.

6.21 *Red Palm Weevil* Rhynchophorus ferrugineus

Toddy along with yeast and acetic acid when smeared on coconut log attracted higher number of *R. ferrugineus* adults. Sugarcane molasses and toddy were also used in Tamil Nadu during a severe infestation to trap the weevils. *R. ferrugineus* weevils are opportunistic oligophages to early fermenting volatiles. Adults on feeding the palm tissue produce an aggregation pheromone (4-methyl-5-nonanol) that attract their conspecifics. Evidence of male produced aggregation led to synthesis of aggregation pheromone 4-methyl-5-nonanol and 4-methyl-5 nonanone (9:1) by Hallet et al. (1993). Methyl-5-nonanol (ferrugineol) developed by Grignard reaction with butyl magnesium bromide and 2 methyl pentanal attracted the weevil (Gunawardena & Bandarage, 1995). The RPW pheromone 4-methyl-5-nonanol and 4-methyl-5 nonanone (9:1) are loaded into dispensers ranging from polymer membrane, polypropylene vials, glass capillaries, alginate beads, thermoplastic spatula, plastic cans, low density polyethylene (LDPE) vials and polyethylene (PE) vials. Area wide management of the weevil in Kerala by mass trapping revealed that 74% of the trapped weevils were females (Jayanth et al., 2007). Trapping of females prior to oviposition will help down to scale down newer infestations. Addition of food baits (banana, sugarcane, coconut petiole) along with aggregation pheromone in the trap increased the trapping efficiency (Vibina & Subaharan, 2019a). The volatiles (kairomones) released from host plant tissues or food baits act synergistically with aggregation pheromone increasing the trap catch. Addition of water to food baits in the pheromone trap aids in fermentation, thereby releasing the volatile organic compounds that attract of RPW adults. Addition of ethyl acetate to the pheromone trap along with fermenting food baits increased the performance of the opening a new avenue into the use of synthetic chemicals replacing the food baits. Fermenting neera when used in tandem with aggregation pheromone trapped higher number of weevils (53.2/trap) suggesting its possibilities in the use of RPW management (Vibina & Subaharan, 2019b). Blend of plant volatiles consisting of alcohols, aldehyde and esters synergized aggregation pheromone in *Rhynchophorus* spp. Synergism between ferrugineol, host palm and food bait has been demonstrated both in coconut. Food volatiles (banana, pineapple, coconut petiole) trapped by headspace volatile entrapment assay loaded in a polypropylene tube when used in coconut plantation @1–2 trap/ha trapped higher number of weevil (Vibina & Subaharan, 2019a). Mass trapping is effective in the case of male-emitted pheromone system that attracts females such as weevils (red palm weevil) and snout beetle. In this system, females are trapped, thus mass trapping directly reduces egg laying. Several tactics are adopted for managing the date palm weevil *R. ferrugineus*. Faleiro (2006) used a tactic based on coupling male aggregation pheromone (4-methyl-5-nonanol), and other semiochemical attractive substances (4-methyl-5-nonanone) which are recorded as kairomones (plant volatile origin). Such a combination has been shown to be synergistic for controlling this insect by monitoring and mass trapping tactics.

6.22 White Grubs—Holotrichia *spp.*

Behavioural control has been successfully applied in the management of carabid beetles. Aniline and ansidine are known as common attractants for white grubs. Aniline has been used as attractant for *Holotrichia* spp. Several companies in India are manufacturing traps and dispensers for *Holotrichia* which are used for trapping them in groundnut and coconut fields.

6.23 Coffee White Stem Borer Xylotrechus quadripes

In case of coffee white stem borer, male produced sex pheromone, (S)-2-hydroxy-3-decanone was identified as the major and potent component for female. In India, pheromone traps can successfully trap the both male and female beetles when installed in cross-vane traps @ 10/acre (Hall et al., 2006). Although the behaviour of the beetles from both China and India is similar, larger plantation area and greater CWSB population density in India may have contributed to a higher pheromone trapping of females, compared to China. The authors have developed an economical dispenser using soft material which needs 30% of the quantity of the pheromone. Based on the volatile composition of arabica coffee several plant volatiles were tested in the field for their attraction to *X. quadripes*. Alpha pinene-based dispensers @ 75 mg gave almost same attraction like the pheromone (Unpublished data of the authors). An inorganic repellent formulation was commercialized from IIHR which gave excellent control when applied prophylacticly during the pre-monsoon (April–May) and post-monsoon (October–November) coinciding with the flight period of the adults. An organic repellent formulation without any salts and with only plant compounds was developed and commercialized by the authors for the organic coffee growers (Verghese et al., 2017c).

6.24 *Coffee Berry Borer*—Hypothenemus hampei

Response of coffee berry borer, *H. hampei*, Ferrari to host volatiles and their role in monitoring and management has been studied in detail (Da Silva et al., 2006; Saravanan & Chozhan, 2003). Simple ethyl alcohol-based attractants has been widely used in the management of *H. hampei* in India.

6.25 *Oil Palm Bunch Moth*—Tirathaba mundella

In case of oil palm bunch moth *T. mundella* Wlk., identification and testing of male sex pheromone components, *viz.* (3S, 6S)-2,2,6-trimethyl-6-vinyl-tetrahydro-pyran-3-ol,4-hydroxy-3-methoxy-benzaldehyde(=vanillin), 6,10,14-trimethyl-2-pentadecanone and 6,10, 14-trimethyl-2-pentadecanol elicited antennal responses in female antenna.

6.26 *Cardamom Shoot and Capsule Borer*—Conogethes punctiferalis

Semiochemical work on *C. punctiferalis* is directed extensively on the sex pheromones in order to monitor moth populations. The calling behaviour and attractive responses of male *C. punctiferalis* to the female crude extract and synthetic blend was studied in detail by Rajabaskar and Regupathy (2012) who found that attraction of male moths to synthetic blend (E-10-hexadecenal and Z-10-hexadecenal) was maximum at 90:10 and followed by 80:20 ratio. However, the field trapping studies by JinKyo et al. (2000) revealed the best attraction of males to blend at 70:30 ratio of E-10-hexadecenal and Z-10-hexadecenal for hair pencil extrusion and at 80:20 ratio for the flying upwind response with the highest attractiveness in fields between 70:30 and 80:20.

6.27 Cigarette Beetle **Lasioderma serricorne**

Apart from field pests, the stored-product pests are also responsible for tremendous damage and economic losses during post-harvest phase of spices. Of which in the cigarette beetle, *L. serricorne*, also known as the tobacco beetle, synthetic serricornin (4,6-dimethyl-7-hydroxy-nonan-3-one), a female sex pheromone is commercially available (Chuman et al., 1985) with noted variation in the chemical and isomeric purity of synthetic compound based on manufacturer.

6.28 Termites

Termites are serious problems during March–April on the shadow trees in coffee/tea orchards and they harbour pepper vines destroying age old trees which takes decades to replace. Though chemical insecticides are available for the management, a plant-based repellent formulation was developed and commercialized by the authors which when applied protects the trees for 4–6 months.

7 Advantages of Semiochemicals

The development of integrated pest management (IPM) strategies is increasing since many problems appeared with the use of synthetic pesticides. Semiochemicals—informative molecules used in insect–insect or plant–insect interaction—are more and more considered within IPM strategies as alternative or complementary approach to insecticide treatments. There are many advantages of using semiochemicals in IPM strategies such as: their high volatility allows diffusion for long distances, application in low concentrations, and rapid dissipation that reduces health and environmental risks compared with chemical pesticides.

- This technology is associated with species specificity, safety to non-target organisms, ease of use and efficacy. Especially pheromone application technology (PAT) is found highly suitable and the one and only ideal tool for control of insect pests like leaf miners, fruit flies, webbers, fruit borers, dwellers and storage pests. Insect pheromones, with their unique mode of action, provide appropriate and effective management for these pests targeting the adult insects.
- In fact, PAT is a powerful tool in Integrated pest management (IPM) strategies and brings about a long-term reduction in pest populations that cannot be accomplished with conventional insecticides.
- Semiochemicals are harmless to the environment, human and other animals because they are naturally existing chemicals and are used in very low volumes compared to insecticides.

- Indeed, these compounds do not present any related adverse effect on the beneficial organisms.
- PAT technology avoids risk of pest insect resistance as observed with insecticides.
- Pheromones in IPM programmes proved mainly to rationalize the use of conventional insecticides with the reductions of up to 50%.
- Pheromone application is best suitable in organic farming as they are complementary to other control strategies.
- Pheromones are complementary to natural enemies, in fact the populations of beneficials grow several times in the field where mating disruption is adopted. The microbial insecticides can be easily used along with the pheromone without any effect on the microbial insecticides.
- Pheromones are the essential and accurate tool for quarantine monitoring and regular monitoring of start of the incidence enabling the farmers to take decision on the management strategies.

References

Abd El-Ghany, N. M., Abdel-Wahab, E. S., & Ibrahim, S. S. (2016). Population fluctuation and evaluation the efficacy of pheromone- based traps with different colour on tomato leafminer moth, *Tuta absoluta* (Lepidoptera: Gelechiidae) in Egypt. *Research Journal of Pharmaceutical, Biological and Chemical Sciences, 7*(4), 1533–1539.

Bakthavatsalam, N., & Singh, S. P. (1996). L-tryptophan as an ovipositional attractant for *Chrysoperla carnea* (Stephens) (Neuroptera: Chrysopidae*). Journal of Biological. Control, 10*, 21–27.

Bakthavatsalam, N., & Singh, S. P. (1999). Behavioural responses of larvae of *Chrysoperla carnea* (Stephens) to kairomones. *Journal of Insect Science, 12*(1), 34–36.

Bakthavatsalam, N., Singh, S. P., Tandon, P. L., Chaudhary, M., & Preethi, S. (1999). Behavioural responses of key parasitoids of *Opisina arenosella* Walker (Lepidoptera: Noctuidae) to the kairomones. *Journal of Biological Control, 3*(1/2), 7–14.

Bakthavatsalam, N., Singh, S. P., Tandon, P. L., Chaudhary, M., & Preethi, S. (2000). Synomone mediated behavioural responses of *Chrysoperla carnea* (Stephens) (Neuroptera: Chrysopidae) to cotton infested by *Helicoverpa armigera* (Hubner) (Lepidoptera:Noctuidae). *Journal of Biological Control, 14*(2), 1–6.

Bakthavatsalam, N., & Tandon, P. L. (2006a). Kairomones, their optimum concentrations, and application techniques to enhance the parasitization efficiency of *Trichogramma chilonis* Ishii (Hymenoptera: Trichogrammatidae). *Journal of Biological Control, 20*(2), 169–174.

Bakthavatsalam, N., & Tandon, P. L. (2006b). Influence of strain variation and kairomonal compounds on the parasitising efficiency of *Trichogramma chilonis*. *Journal of Biological Control, 20*(1), 13–18.

Bakthavatsalam, N., & Tandon, P. L. (2007). Behaviour and electrophysiological responses of C*hrysoperla carnea* (Stephens) to kairomones-acid hydrolysed/ oxidised L-tryptophan and its breakdown products. *Journal of Biological Control, 21*(special issue), 79–84.

Bakthavatsalam, N., Verghese, A., & Shivananda, T. N. (2017a). Dorsalure-plant volatile composition to increase the trap efficiency for mango fruit flies. Patent filed

Bakthavatsalam, N., Verghese, A., & Shivananda, T. N. (2017b). Method for attracting both the sexes of *Bactrocera dorsalis* insect using delta trap. Patent fied

Bakthavatsalam, N., Verghese, A., & Shivananda, T. N. (2017c). Dorsa-delta—A trap for mango fruit fly. Patent filed.

Basavaraj, K., Geetha, S., Jagadish, K. S., Naik, M. I., & Shadakshari, Y. G. (2013). Influence of meterological factors on sex pheromone trap catches of Helicoverpa armigera (hub) and Spodoptera litura (Fab.) in sunflower (Helianthus annus). *Current Biotica, 7*(3), 174–182.

Bouslama, T., Laarif, A., Soltani, A., Chaieb, I., Amri, M., & Rhouma, A. (2019). Screening chickpea lines and varieties for a possible resistance or tolerance to the pod borer *Helicoverpa armigera*. *Tunisian Journal of Plant Protection, 14*(1), 69–81.

Bruce, T. J., & Cork, A. (2001). Electrophysiological and behavioral responses of female *Helicoverpa armigera* to compounds identified in flowers of African marigold, *Tagetes erecta*. *Journal of Chemical Ecology, 27*, 1119–1131.

Budenberg, W. J., Ndiege, I. O., Karago, F. W., & Hansson, B. S. (1993). Behavior and electrophysiological response of the banana weevil, Cosmopolites sordidus to host plant. *Journal of Chemical Ecology, 19*, 267–278.

Chuman, T., Mochizuki, K., Mori, M., Kohno, M., Kato, K., & Noguchi, M. (1985). *Lasioderma* chemistry, sex pheromone of cigarette beetle (*Lasioderma serricorne* F.). *Journal of Chemical Ecology, 11*, 417–434.

Da Silva, F., Ventura, M. U., & Morales, L. (2006). Capture of *Hypothenemus hampei* Ferrari (Coleoptera, Scolytidae) in response to trap characteristics. *Scientia Agricola, 63*, 567–571.

El Shafie, H. A. F., & Faleiro, R. (2017). Semiochemicals and their potential use in pest management. In V. D. C. Shield (Ed.), *Biological control of pest and vector insects*. Intech Open.

Faleiro, J. R. (2006). A review of the issues and management of the red palm weevil *Rhynchophorus ferrugineus* (Coleoptera: Rhynchophoridae) in coconut and date palm during the last one hundred years. *International Journal of Tropical Insect Science., 26*, 135–150.

Fite, T., Damte, T., Tefera, T., & Negeri, M. (2020). Evaluation of commercial trap types and lures on the population dynamics of Helicoverpa armigera (Hubner) (Lepidoptera: Noctuidae) and its effects on non- target insects. *Cogent Food & Agriculture, 6*(1). https://doi.org/10.1080/23311932/2020.1771116

Gibb, A. R., Pinese, B., Tenakanai, D., Kawi, A. P., Bunn, B., Ramankutty, P., & Suckling, D. M. (2007). (Z)-11-Hexadec- enal and (3Z,6Z,9Z)-Tricosatriene: sex pheromone components of the red banded mango caterpillar *Deanolis sublimbalis*. *J Chem Ecol, 33*, 579–589.

Guédot, C., Horton, D. R., & Landolt, P. J. (2009). Attraction of male winter form pear psylla to female-produced volatiles and to female extracts and evidence of male-male repellency. *Entomologia Experimentalis et Applicata, 130*, 191–197.

Gunawardena, N. E., & Bandarage, U. K. (1995). 4-Methyl-5-nonanol (ferrugineol) as an aggregation pheromone of the coconut pest, *Rhynchophorus ferrugineus* F. (Coleoptera: Curculionidae): Synthesis and use in a preliminary field assay. *Journal of the Natural Sciences Council of Sri Lanka,* ***23***, 71–79.

Haldhar, S. M., Karuppaiah, V., Muralidharan, C. M., & Sharma, S. K. (2015). Insect-pests of date palm and their management. In A. K. Pandey & Pramod (Eds.), *Insect pests management of fruit crops* (pp. 405–421). Mall Biotech Books.

Hall, D. R., Cork, A., Phythian, S. J., Chittamuru, S., Jayarama, V. M. G., Sreedharan, K., Seetharama, H. G., Vinod Kumar, P. K., & Naidu, R. (2006). Identification of components of male-produced pheromone of coffee white stemborer, *Xylotrechus quadripes* Chevrolat (Coleoptera: Cerambycidae). *Journal of Chemical Ecology, 32*(1), 213–237.

Hallet, R. H., Gries, G., Gries, R., Borden, J. H., Czyzewska, E., Oehlschlager, A. C., Pierce, H. D., Angerilli, N. P. D., & Rauf, A. (1993). Aggregation pheromones of two Asian palm weevils, *Rhynchophorus ferrugineus* and *R. vulneratus*. *Naturwissenschaften, 80*, 328–331.

Heath, R. R., Coffelt, J. A., Sonnet, P. E., Proshold, F. I., Dueben, B., & Tumlinson, J. H. (1986). Identification of a sex pheromone producted by female sweet potato weevil, *Cylas formicarius elegantulus* (Summers). *Journal of Chemical Ecology, 12*, 1489–1503.

Jayanth, K. P., Mathew, M. T., Narabenchi, G. B., & Bhanu, K. R. M. (2007). Impact of large-scale mass trapping of red palm weevil *Rhynchophorusferrugineus* Olivier in coconut plantations in

Kerala using indigenously synthesized aggregation pheromone lures. *Indian Coconut Journal, 38*, 2–9.

JinKyo, J., Han, K. S., Choi, K. S., & Boo, K. S. (2000). Sex phero- mone composition for field-trapping of *Dichocrocis punctiferalis* (Lepidoptera: Pyralidae) males. *Korean J Appl Entomol, 39*, 105–110.

Juneja, R. P., Parmer, G. M., Gheelani, Y. H., Munga, K. D., Patel, P. R., & Charlahari, N. N. (2015). Monitoring of earhead worm Helicoverpa armigera (Hubner) through sex pheromone in pearl millet. *International Journal of Plant Protection, 8*(2), 245–249.

Kamala Jayanthi, P. D., 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 A. K. Chakravarthy (Ed.), *New horizons in insect science: Towards sustainable pest management* (pp. 237–257). Springer India. https://doi.org/10.1007/978-81-322-2089-3_22

Li, P., Zhu, J., & Qin, Y. (2012). Enhanced attraction of *Plutella xylostella* (Lepidoptera: Plutellidae) to pheromone baited traps with the addition of green leaf volatiles. *Journal of Economic Entomology, 105*, 1149–1156.

Lo, P. L., Walker, J. T. S., Horner, R. M., & Hedderley, D. I. (2013). Development of multiple species mating disruption to control codling moth and leafrollers (Lepidoptera: Tor- tricidae). *New Zealand Plant Protection, 66*, 264–269.

Morrison, W. R., Lee, D. H., Reissig, W. H., Combs, D., Leahy, K., Tuttle, A., Cooley, D., & Leskey, T. C. (2016). Inclusion of specialist and generalist stimuli in attract-and-kill programs: The irrelative efficacy in apple maggot fly (Diptera: Tephritidae) pest management. *Environmental Entomology, 45*(4), 974–982. https://doi.org/10.1093/ee/nvw043

Padmanaban, B., & Lakshmi Balaji, A. (2010). Evaluation of entomopathogenic nematode, *Heterorhabditis indica* for the management of Banana corm weevil, *Cosmopolites sordidus* (Germar). *Paper presented in National Conference on Production of Quality seeds and Planting material, Health management in Horticultural crops*, 11–14 March 2010, New Delhi.

Pagadala Damodaram, K. J., Kempraj, V., Aurade, R. M., Venkataramanappa, R. K., Nandagopal, B., Verghese, A., et al. (2014). Oviposition Site-Selection by *Bactrocera dorsalis* Is Mediated through an Innate Recognition Template Tuned to γ-Octalactone. *PLoS One, 9*(1), e85764. https://doi.org/10.1371/journal.pone.0085764

Palanichamy, M. G., & Ya-Ping, Z. (2011). Identifying potential pitfalls in interpreting mitochondrial DNA mutations of male infertility cases. *Indian J Med Res, 134*, 447–451.

Palaniswami, M. S., Sreeja, V. G., & Roshan, C. J. (2000). A potent kairomone for the management of sweet potato weevil *Cylas formicarius* F. *Entomon, 25*, 269–280.

Rajabaskar, D., & Regupathy, A. (2012). Calling behavior and attractive response of cardamom shoot and capsule borer *Conogethes punctiferalis* Guenee (Lepidoptera: Pyralidae) to the female crude extract and synthetic blend. *Journal of Entomology, 9*, 296–301.

Rajasekhara Rao, K., Naskar, S. K., Palaniswami, M. S., & Ray, R. C. (2010). Management of sweet potato weevil, *Cyclas formicarius* (Fab.): An overview. *Journal of Root Crops, 36*, 14–26.

Raman, K. V. (1988). Control of potato tuber moth *Phthorimaea operculella* with sex pheromones in Peru. *Agriculture, Ecosystems, & Environment, 21*, 85–89.

Ravi, G., & Palaniswami, M. S. (2002). Evidence for a female produced sex pheromone in the banana pseudostem weevil, *Odoiporus longicollis* Oliver. *Current Science, 83*(7), 893–898.

Ray, A. M., Zunic, A., Alten, R. L., McElfresh, J. S., Hanks, L. M., & Millar, J. G. (2011). Cis-vaccenyl acetate, a female- produced sex pheromone component of *Ortholeptura valida* a long horned beetle in the subfamily Lepturinae. *Journal of Chemical Ecology, 37*(172–178), 699–670.

Reddy, G. V., Fettkother, R., Noldt, U., & Dettner, K. (2005). Enhancement of attraction and trap catches of the old- house borer, *Hylotrupes bajulus* (Coleoptera: Cerambycidae), by combination of male sex pheromone and monoterpenes. *Pest Management Science, 61*.

Saravanan, P. A., & Chozhan, K. (2003). Monitoring and management of coffee berry borer, *Hypothenemus hampei* Ferrari (Scolytidae: Coleoptera). *Crop Research, 26*, 154–158.

Seema, W. (2009). Biotechnological approaches in the management of plant pests, diseases and weeds for sustainable agriculture. *Journal of Biopesticides, 2*, 115–134.

Shah, K. D., Jhala, R. C., & Dhandge, S. R. (2017). Standardization of pheromone traps for the mass trapping of *Helicoverpa armigera* (Hubner) Hardevic in tomato. *Current Agriculture Research, 5*(1). https://doi.org/10.12944/CARJ5.1.05

Ujjan, R. L., Mushtaq, A., Zachi, A., & Alhilfi, A. (2019). Performance of pheromone traps at different height for mass trapping of *Helicoverpa armigera* (Noctuidae: Lepidoptera) in chick pea field. *Asian Journal of Agriculture and Biology, 7*(4), 610–616.

Verghese, A., Bakthavatsalam, N., & Shivananda, T. N. (2017a). Protocol for alcohol free plywood laced melon fly attractant. Patent filed

Verghese, A., Bakthavatsalam, N., & Shivananda, T. N. (2017b). Repter—A herbal based repellent for termites on woody trees. Patent filed

Verghese, A., Bakthavatsalam, N., & Shivananda, T. N. (2017c). Herbal swabber for the revival of coffee plants infested with stem borer. Patent filed

Verghse, A., Shivananda, T. N., & Jayanthi, P. D. K. (2014). *Integrated management of mango fruit fly (Bactrocera spp.)*. IIHR Extension Folder, Indian Institute of Horticultural Research. 4 p.

Vibina, V., & Subaharan, K. (2019a). Olfactory response of red palm weevil, *Rhynchophorusferrugineus* (Olivier) (Coleoptera: Dryophthoridae) to host/ food volatiles. *Journal of Plantation Crops, 47*(1), 43–47.

Vibina, V., & Subaharan, K. (2019b). Electrophysiological and behavioral response of red palm weevil, *Rhynchophorusferrugineus* (Olivier) (Coleoptera: Dryophthoridae) to host/food volatiles. *Journal of Plantation Crops, 47*(2), 82–89.

Yasuda, K., Hongo, T., & Etoo, N. (2004). A new type of pheromone formulation with visual stimulation for control of sweet potato weevil, *Cylas formicarius* (Fab.). *Japanese Journal of Applied Entomology and Zoology, 48*, 87–93.