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REVIEW ARTICLE

Semiochemical techniques for the management of coconut insect pest

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Abstract

Semiochemicals are chemical substances utilized by insects use to modify their physiology and behaviour and are classified as pheromones (intraspecific effects) and allelochemicals (interspecific effects). It plays a crucial role in Integrated Pest Management (IPM) as a marker of insect presence and a behavioural modifier that prevents pest dissemination and multiplication. Insect populations can be managed using various attractant-based strategies such as monitoring, mass trapping and attracting insect pests. These management methods require understanding insect chemical ecology and identifying the cues involved. Semiochemicals for managing key insect pests of coconut have been extensively studied. However, practical utility and awareness among farmers are limited. Major coconut pests are managed with effective and efficient attractants, pheromones and host volatiles. Semiochemical applications are gaining importance as a primary management strategy and provide significant scope for sustainable and eco-friendly pest management. Despite the noteworthy strides in developing semiochemical-based pest management approaches for coconut, a critical gap exists for further innovations to evolve solutions applicable to a broader array of significant pests and establish sustainable and highly effective pest management strategies. In light of this, the use of semiochemical techniques for sustainable pest management in coconut plantations is extensively discussed in this review.

Keywords

Oryctes rhinoceros; *Opisina arenosella*; pheromones; *Rhynchophorus ferrugineus*; semiochemicals

Introduction

The coconut palm, *Cocos nucifera* L., belongs to the Arecaceae: Arecales and is a versatile palm valued for culinary and medicinal use (1-3). Coconut is grown in over 93 countries worldwide in 12.25 million hectares, with an annual production of 66674 million tonnes of nuts. India is the leading producer of coconut in the world with a total output of 20736 million nuts with a productivity of 9430 nuts/ha, followed by the Philippines with a production of 14717 million nuts and Indonesia with 14200 million nuts (4). Among the Indian states, Karnataka occupied first place with the production of 5949.46 million nuts and its Southern neighbour Kerala occupied the second position with 5628.42 million nuts, followed by Tamil Nadu with 5421.76 million nuts in the year 2022-23 (4). In India, coconut cultivation spans more than 2199 lakh hectares, involving more than 10 million individuals in activities such as cultivation, post-harvest processing and marketing (3). Numerous abiotic and biotic factors contribute to constraints on coconut plantations in the country (5). Although approximately 750 insect pest species have been reported on coconut palms (6), only a few numbers of pests are economically significant (7). Existing approaches to manage infestations involve cultural, mechanical, physical and chemical management methods. However, detecting insect pests on the palm challenges due to the tall nature of coconut palms, concealed habitats and year-round food availability, which are significant risks to coconut palms (8). Understanding the chemical ecology of pests provides valuable insights into adopting appropriate strategies. Semiochemicals, which are species-specific and non-toxic to the environment, are particularly promising. Identifying pheromones and other attractive semiochemical agents enables the timing of chemical applications, allowing for managing a wide range of pests. Compared to conventional pest management methods, semiochemicals offer a practical, economically sound and ecologically compatible strategy. This review article discusses the semiochemicals for managing key insect pests of coconut and its concepts. We explored the opportunities and challenges of implementing semiochemicals and highlighted the need for future development.

Overview of Key Pests of Coconut

Coconut palms deal with many threats from various pests and diseases, significantly reducing yield and a report of 110 coconut pest species was recorded (9). Later, an investigation by ICAR - Central Plantation Crops Research Institute (CPCRI) in 1979 uncovered a more extensive list- over 800 insects and mites, 173 fungal pathogens and 78 nematode species that harm coconut cultivation. Insect, mite and vertebrate pests can cause up to 30% yield loss (10). Among the various insect orders, Coleoptera is the most common and primary group, with 323 species found to infest coconut palms (11). Beetles cause more damage than other pests. They mostly damage leaves, roots and crown regions. Curculionidae, Chrysomelidae and Scarabaeidae are the most damaging pest groups, causing frond loss and palm damage (12). Lepidopterans are another serious pest of coconut, causing leaf and inflorescence damage(8).

Key pests of coconut

Red palm weevil (RPW), *Rhynchophorus ferrugineus* Olivier (Curculionidae: Coleoptera)

RPW was first described as a destructive insect in the Indian coconut palm (13). In India, RPW inflicts damages on approximately 12% of young coconut palms aged between 5 to 20 years (14). RPW infests nearly 40 different palm species (15). The nature of damage includes yellowing and wilting of the inner and middle whorl of leaves, small circular holes, oozing out of a brown viscous fluid that can be seen on the trunk portion (Fig. 2A), fermented odour, longitudinal splitting of leaf base, the gnawing sound of grubs, chewed up fibres at the leaf axil, resulting in the toppling of the crown (Fig. 2B) (16). Over the period, the trunk becomes tunnelled, weaker and may topple down (6).

Coconut Rhinoceros beetle, (CRB) *Oryctes rhinoceros* Linnaeus (Scarabaeidae: Coleoptera)

CRB is a significant pest of coconut and oil palms but also attacks other palm species. Adult beetles feed on developing palm fronds at night, causing unique V-shaped incisions in the emerging fronds (Fig. 3). The central spindle portion appears to be toppled and chewed fibres can be seen. Frequent attacks on the palms will reduce productivity and may kill the palms in severe conditions. Recently, CRB has been spotted entering newly transplanted coconut seedlings and consuming the growing spear leaf, causing wilting and poor seedling establishment. Farmers tend to uproot the malformed seedlings when twisted, causing elephant tusk-like symptoms and stunted growth (16). The odour emanation from wounded areas' is a common cause of recurring attacks on the seedling (16).

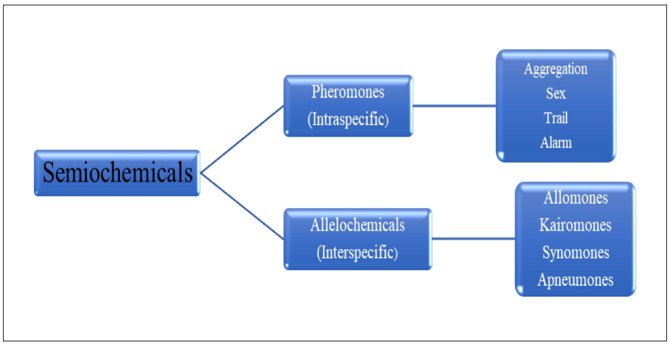

Fig. 1. Classification of semiochemicals.

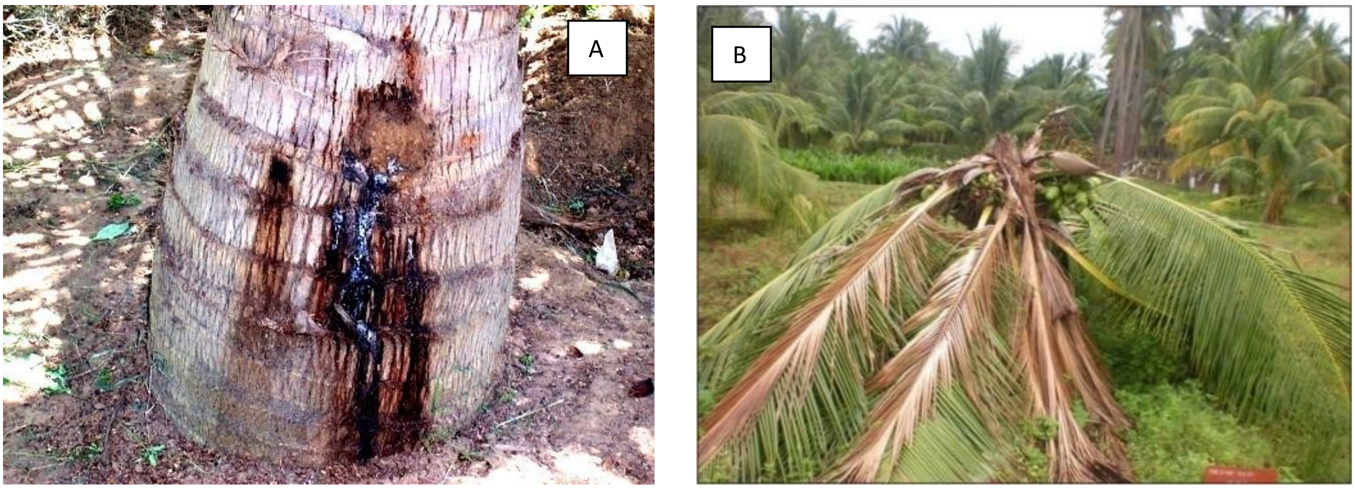

Fig. 2. A. Oozing out of brown viscous fluid B. The toppling of the crown.

Fig. 3. Typical coconut rhinoceros beetle damage symptoms (V-shaped incisions in the emergent fronds).

The Black-headed caterpillar (BHC), *Opisina arenosella* Walker (Xyloryctidae: Lepidoptera)

BHC is a significant defoliator of coconut palms. In India, BHC was discovered in 1907 on Palmyrah palms in Tamil Nadu and coconut leaves in Andhra Pradesh in 1909 (17). Several palm species, including ornamental palms and crops like bananas, cashews, and jack, have been identified as potential hosts (17, 18). Infested palms have dried-up patches on the leaflets (Fig. 4A) and galleries of silk and frass on the underside of the leaflets are observed (Fig. 4B). In severe circumstances, this outbreak causes a scorched appearance owing to leaf drying. Damaged leaves droop, bunches buckle and immature nuts shed significantly (19).

Coconut scale, *Aspidiotus destructor* Signoret (Diaspididae: Hemiptera)

Coconut scale has a broad range of hosts, with more than 60 families that found worldwide in tropical and subtropical locations (20, 21). The vivid yellow colour of injured coconut palms is apparent from a long distance. In extreme circumstances, the leaves dry up, entire fronds fall off and the crown dies. Heavy infestation stunts palm, reduces yield or causes crop failure.

Whiteflies

Within India, the coconut agroecosystem has faced significant disruptions in the past five years due to the invasion of four exotic whitefly species, including the rugose spiralling whitefly (*Aleurodicus rugioperculatus* Martin), Bondars' nesting whitefly (*Paraleyrodes bondari* Peracchi), Nesting whitefly (*Paraleyrodes minei* Iaccarino) and Neotropical whitefly (*Aleurotrachelus atratus* Hempel). All these species have caused substantial damage. The Rugose spiralling whitefly (RSW) (*Aleurodicus rugioperculatus*) (Aleurodidae: Hemiptera) was described by Martin from Belize in Central America in 2004 (22). The RSW is polyphagous and found to feed more than 118 host plants belonging to 43 plant families of economically important crops in the United States (12). RSW was noticed in a severe form in coconut palms in Pollachi, Coimbatore district, Tamil Nadu, India during August- September 2016 (23), Chenganassery, Kottayam District, Kerala in India (24) and other parts of the country. Both nymphs and adult whitefly suck the sap by their sucking-feeding habit and siphon out coconut sap by selective feeding from the abaxial of the coconut leaflets. De-sapping by RSW would induce stress on the palms due to removing water and nutrients, but neither colour change nor necrosis of leaflets has been reported (25). When insects feed extensively, they release honeydew, which can end up on the upper side of leaves and other crops beneath them. During severe attacks, egg spirals can be seen on the petioles and tender nuts. Honeydew is sweet and watery, attracting ants and promoting fungus growth, which damages leaves and affects the plants' ability to photosynthesize efficiently. *A. rugioperculatus*, which is native to the neotropical region, has become the predominant species in terms of both size and damage. It has also extended its range into the Oriental region, initially reported in Kottayam District in August 2016 (24). Within five years, this insect has spread throughout Tamil Nadu, causing significant damage to coconut palms. Subsequently, *P. bondari* was reported in Kayamkulam (26) and expanded more rapidly than *A. rugioperculatus*, colonizing nearly all coconut plantations in Tamil Nadu within two years. The other two species, *P. minei* and *A. atratus*, have been observed in specific northwestern locations in Tamil Nadu. *Aleurotrachelus atratus*, which exclusively infests palm species, has a wide range of 56 host plants, with coconut being its primary host (27). The other pests of coconut, their distribution, life cycle and nature of damage are listed in Table 1.

Current Management Practices for Key Pests of Coconut

The accessibility, availability, easy mode of application, and effectiveness of pesticides have led to their widespread adoption as foremost management practices for pest management (41-43). However, the use of pesticides has resulted in the development of insecticide resistance and the accumulation of pesticide residue in harvested commodities

Fig. 4. A. Dried-up patches on the leaflets of the lower leaves; B. Galleries of silk and frass on the underside of leaflets.

Table 1. The pests of coconut, distribution, life cycle and nature of the damage

Order	Family	Pest	Distribution	Life cycle	Nature of damage	Reference
Coleoptera	Melolonthidae	White grub *Leucopholis Coneophora* Burmeister	Southern parts of peninsular India	12 months	Leaves turn yellow and premature nut shedding. Flowering delayed.	(28, 29, 30)
Lepidoptera	Hesperiidae	Coconut Skipper *Gangara thyrsis* Moore *Suastus gremius*	All over peninsular India	2 months	One-half of the leaflets are cut and rolled into a case. Tip of leaflets rolled	(31, 29, 32, 30)
	Limacodidae	Slug caterpillar *Parasa lepida Cram, Contheyla rotunda Harm and Macroplectra nararia* Moore	South East Asian region, West coast, Godavari district in India	20-30 days	Defoliation, leaving only the midrib and veins.	(33, 34, 19, 32)
Hemiptera	Pseudococcidae	Long-tailed Mealybug *Pseudococcus longispinus*	America, Africa, Europe	1-2 months	Central leaves stunted, deformed, and	(35, 36)
	Tingidae	Lacewing bug *Stephanitis typicus* Distant	India, Sri Lanka, much of Southeast Asia, and the tropical West Pacific	32-60 days	Appearance of white spots on the upper surface of leaves.	(37)
		Coconut Eriophyid mite *Aceria guerreronis* Keifer	Americas, Africa, and Southeast Asia.	7-10 days	Triangular pale or yellow and brown patches close to the perianth. Longitudinal fissures and splits. Oozing of the gummy exudation from the affected surface. Reduced size and copra content. Malformed nuts with cracks and hardened husk.	(36, 38, 39)
		Termites *Odontotermes Obesus*	South Asia	6-12 months	Wilting of seedlings. The base of the trunks is plastered with runways made of fibres and soil.	(40)

such as tender coconut and copra, which are often consumed without processing (44, 45) and the damaging effects on beneficial organisms (7). Integrated Pest Management (IPM) practices have proven effective pest management in the coconut ecosystem (15). IPMs' foundation involves understanding the biology and ecology of pests, conducting pest sampling and monitoring, determining economic thresholds and applying various management strategies such as chemical, biological and microbial control (11). Among the different components of IPM practices, monitoring and mass trapping and destroying insect pests with lures, i.e. semiochemicals in insect pest management, is the evergreen strategy, which would be harmless to natural enemies and the ecosystem. Semiochemicals offer a promising approach to coconut pest management, aligning with sustainable agriculture goals by promoting ecological balance.

Importance of Semiochemicals

Strategies based on semiochemicals have emerged as a crucial component of IPM. The efficacy of diffusing widely despite small, released quantities, incorporating semiochemicals into IPM strategies holds great potential (46). Semiochemicals can serve as highly target-specific management tools in the IPM component, mainly when the pest population is minimal, conventional pesticide applications are impractical or ineffective and where reaching the target pest with insecticides poses challenges. In such scenarios, strategies involve attracting many pests to decrease their population or disrupting mating patterns to hinder reproduction. Various methods, like mass trapping, attract-and-kill, attract-and-infect, or push-pull approaches, may be employed to mass elimination of the pest population. The effectiveness relies on the efficient attraction of one or both sexes, preferably females. Communication disruption, causing disorientation and confusion, is key in preventing successful encounters between the sexes, consequently reducing mating and reproductive success (12).

Classification of Semiochemicals

The term "semiochemicals" initially refers to chemicals utilized for both intra-species and inter-species communication, encompassing signals or markers (47). Semiochemicals can be classified into two main groups: allelochemicals and pheromones (Fig. 1). Allelochemicals mediate the interaction between individuals of different species (interspecific) and pheromones mediate interactions between individuals of the same species (intraspecific interactions). A pheromone is a chemical or a combination of chemicals released externally by an organism, which elicits specific reactions in receiving individuals of the same species (48). Pheromones are further classified as primer effect pheromones, which cause long-term physiological changes and releaser effect pheromones, which cause short-term or instantaneous behavioural responses based on the behavioural reaction. In contrast, allelochemicals are non-nutrient substances originating from an organism that impact the behaviour, physiological condition, or ecological well-being of an organism belonging to a different species (49). Allelochemicals are divided into various classes, *viz*., allomones, kairomones, synomones and apneumones, depending on their specific actions. Kairomones benefit the receiver only, allomones benefit the emitter only and synomones benefit both the emitter and receiver. Pheromones are widespread in pest management and allelochemicals are relatively underutilized. Semiochemicals-based pest management in coconut utilizes allomones and pheromones, which are used for monitoring and mass trapping. These targeted compounds effectively reduce pest damage and population growth, offering a sustainable alternative to broad-spectrum insecticides.

Practical Utility of Semiochemical Mediated Technology for Key Pest of Coconut

Monitoring

Monitoring serves to estimate the pest population. Semiochemicals-baited traps employing pheromones or kairomones represent cost-effective and widely utilized tools for monitoring key insect pests of coconut. These traps effectively detect insect pests and estimate their population density (50). The first known methods for trapping include plant resources such as wounded coconut trunks and palm logs, compost and fruit branches to attract insects. These supplies and the caught beetles were eventually discarded (51). The efficacy of pest monitoring relies on the deployment of suitable dispensers containing precise blends of pheromone compounds strategically positioned in traps at optimal densities ranging from one to two per acre in appropriate locations within the fields (52). It is crucial to monitor the key pests of coconut, including RPW, CRB and BHC. RPW activity to safeguard palm trees from infestation and the oviposition and egg-hatching period can vary depending on average temperatures (7, 53, 54). A significant 1.5-fold increase in *O. rhinoceros* trap catch was recorded following the installation of the pheromone traps (51). Decisions regarding pest management strategies, including chemical management methods and the release of natural enemies, are often decided based on the pheromone trap catches (55). However, despite the widespread use of pheromone-based monitoring, a common challenge arises wherein the quantity of insects captured in traps does not always reliably reflect the actual insect populations in the field.

Mass trapping

The mass trapping approach helps to reduce the pest population. Managing of insect pests involves utilizing attractants of the targeted species and eliminating the attracted pests from the natural population. Mass trapping, functioning as a mechanical control strategy, follows monitoring procedures and reduces the densities of insect pests (56, 57). Mass trapping of insect pests is accomplished using pheromone traps and light traps.

Mass-trapping of adult BHC moths is commonly practiced in India using light traps and water-filled trays below a halogen light. These traps are effective as BHC adults exhibit strong phototactic behaviour, particularly towards wavelengths of 365-368 nm, from 11:00 pm to 2:00 am (58). Mass trapping directly reduces oviposition by capturing females, which is particularly effective for male-emitted pheromone systems that attract females, such as in RPW.

This density-dependent strategy involves minimizing male and female individuals from the natural pest population, resulting in the slowdown of population growth. Notable instances of success have been documented in managing coconut pests through the combination of aggregation pheromones and food bait (7). According to the severity of the infestation, the number of traps for mass trapping may vary, ranging from one trap for one hectare in areas with lower RPW activity to up to ten traps for one hectare in heavily infested plantations with high RPW activity (59). Mass trapping using pheromone traps effectively reduced *O. rhinoceros* populations in coconut plantations by 78 % across four states in India (Kerala, Karnataka, Tamil Nadu and Andhra Pradesh) over nine months (60). Comparable and favourable results were observed in other studies within the country (51). For example, mass trapping for CRB utilizes the pheromone Ethyl-4-methyl octanoate (E4-MO) (61), while for RPW, 4 Methyl 5 Nonanol and 4 Methyl 5 Nonanonone (9:1) are commercially used (5). Area-wide management of RPW in Kerala through mass trapping revealed that 74% of the captured weevils were females, indicating the potential for reducing new infestations by trapping females before oviposition (62). Using one trap per two hectares and servicing it biweekly to trap adult *O. rhinoceros* reduces weevil damage by over 90 % and is more cost-effective than applying insecticides (55). In conclusion, while mass trapping is promising as a management tool for reducing insect pest populations, its effectiveness and economic viability depend on various factors, including the target pest species, landscape characteristics and scale of implementation

Attract and kill

Various pest management approaches utilize traps baited with either pheromones or kairomones to monitor the population of different pests. One such tactic is the attract-and-kill method, which involves trapping pests simultaneously, causing their demise. The success of this method relies on the potency of the attractant, killing agent and their combination. The attractant should lure insects from a distance and the bait should be distributed strategically to maximize detection by the targeted individuals (males, females, or both). The attractant should not cause mating disruption and should be more appealing than natural attractants (e.g., sex pheromones and host plants). The killing agent should act rapidly to prevent further mating or crop damage and should not repel the pest. If a pheromone produced by females is used as bait to attract males, the concentration of bait per hectare in relation to female density could significantly impact the success of the method, as the bait competes with calling females. E4-MO in a sticky matrix is an attract-and-kill product containing E4-MO and cypermethrin in a sticky matrix is commercially available for CRB (51). Implementing area-wide IPM programs with pheromones should commence when infestation levels are as low as one percent of palms infested (63). The commonly utilized standard four-window bucket trap (7) is widely adopted for trapping this pest. An alternative method for attracting and exterminating RPW adults without bait was evaluated. This method demonstrated trapping efficiency like traditional food-baited pheromone traps in plantations in Saudi Arabia (64). Alongside the pheromone lure, incorporating food bait such as palm tissue, dates, or sugarcane mixed in water within the trap (7, 65) ensures effective synergy between bait and lure, leading to enhanced captures. Remarkable technologies were designed for lure-and-kill applications, combining attractant and killing agents in a bead or paste. This bait, with known concentrations, was either manually applied at a specific density for one hectare or sprayed through hollow fibres from land or air. Lure-and-kill seems more effective against dipterans and coleopterans than lepidopterans (57).

Procedure for Developing Semiochemical

Developing semiochemical products, such as pheromones, entails several stages. These include isolating the pheromone, identifying the principal compound, synthesizing it, identifying an appropriate dispenser, determining the optimal dosage, employing stabilizers, creating suitable traps and evaluating the optimal number of traps with dispensers per unit area for monitoring, mass trapping, mating disruption and male annihilation techniques (MAT) (66, 67). Electrophysiological instruments like the Electroantennogram (EAG), Gas Chromatography Coupled Electro antennogram Detector (GCEAD), Gas Chromatography Coupled Single Sensillum Recorder (GCSSR), Gas Chromatography Coupled Mass Selective Detector (GCMSD), Fourier Transformed Infrared Spectroscopy (FTIR) and Nuclear Magnetic Resonance Spectroscopy (NMR) coupled with various sample preparation techniques, such as Solid-Phase Microextraction Techniques (SPME) have become more sensitive techniques for detecting and analyzing the semiochemicals. If the glandular source of the pheromone is known, the organ can be excised from the female. Despite this, the procedure has significant downsides. The extraction process often results in non-relevant molecules, either in the form of precursors or active compounds or in ratios that differ from the normal makeup of organisms. For these reasons, entrainment or headspace volatile collection is typically preferred. Purified air is passed over organisms in an "aeration chamber" to isolate organisms. The exhaust air sample can then be analyzed by GC-MS or collected on absorbents like Super Q using columns (for large amounts) or SPME. SPME is a solvent-free sample preparation technology that captures volatiles from the surrounding air using a needle-like silica-coated fibre housed within a syringe-like instrument. The fibre is placed into a heated inlet and the substances collected are evaluated using GC or GC-MS. Active compounds are identified using mass spectrometry and Proton Nuclear Magnetic Resonance (PNMR). To identify low concentrations of biologically active tiny signal molecules in a mixture (68) Differential Analysis by 2D NMR spectroscopy (DANS). Well-established semiochemical technology has been developed for Coleoptera and Lepidoptera pests. Identified semiochemicals for major coconut insect pests are described below (Table 2).

Semiochemical Mediated Technologies for Key Pests of Coconut

Aggregation pheromone

RPW, *R. ferrugineus*

IPM practices have proven effective in managing RPW infestation (15). IPM involves surveillance (78), field sanitation, preventing the infestation of CRB and bud rot and avoid mechanical damage on truck during inter cultural operations. Despite the viability of biological control agents, the pests' cryptic nature and timely availability of biological control agents challenge the management of RPW (7). RPW adults produce an aggregation pheromone (4-methyl-5-nonanol) when feeding on palm tissue, which attracts conspecifics. The weevil was drawn to ferrugineol, a product of the Grignard reaction with butyl magnesium bromide and 2 methyl pentanal (52). Ferruginol sustained the efficiency of trapping the weevil even at a low dose of 0.48 milligrams per day, which has proven successful in coconut plantations in India (79). This provides an advantage for managing weevil populations, as the pheromones attract more females that lay eggs, which hatch into grubs that cause damage (7). Replacing the lure in traps if there was 5 % injected in a polymer membrane that

Table 2. Identified semiochemical for key Insect Pests of Coconut

Order	Family	Species	Allelochemical	Reference	Pheromone	Reference
Coleoptera	Curculionidae	Redpalmweevil *Rhynchophorus ferrugineus*	Ethyl alcohol (A) Ethyl propionate (A) Pentan-1-ol (A) 2-methoxy-4-vinyl phenol (A) Gamma-nonanoic lactone (A) α-pinene (R) 1-often-3-ol (R) Geraniol (R)	(69-72, 54)	Male aggregation pheromone, 4S, 5S- nonanol, 4S,5S nonanone	(54) (73) (72)
	Scarabaeidae	Rhinoceros beetle *Oryctes rhinoceros*	Naphthalene balls (R)	(74)	4-ethyl methyl octanoate, ethyl 4-methyl heptanoate, 4-methyl octanoic acid	(65, 75)
Lepidoptera	Xyloryctidae	Black Headed Caterpillar *Opisina arenosella*	Not reported	Not reported	Female sex pheromone ((Z, Z, Z,) – 3,6,9-tricosatriene	(76)
Hemiptera	Diaspididae	Coconut Scale *Aspidiotus destructor*	Propanoic acid	(77)	Not reported	Not reported

survived over 84 days in coconut gardens (80). Nanomaterials offer a regulated spatio-temporal release of semiochemical and increased environmental stability, making them a promising carrier for volatile organic molecules (5). The introduction of nanogel pheromones in the field resulted in a 22.51 % increase in RPW adult catchability (81).

Pheromone synergist

Antennae of the RPW responded to palm esters and propyl acetate by electrophysiological tests (70, 54). Subsequently, a similar study investigated the electrophysiological and behavioural responses of RPW to various food baits, including banana, pineapple and coconut petiole (5). Their findings indicated that banana volatiles elicited the highest EAG response (0.7 mV), followed by pineapple and coconut petiole. Ferrugineol can act synergistically with host palms and food baits in coconut plantations (80, 72). The headspace volatile entrapment assay in a coconut plantation was employed using one to two traps per hectare to capture food volatiles from banana, pineapple and coconut petioles (82). Studies found that lures of 750 and 1000 mg pheromone dosages of RPW and CRB trapped significantly higher weevils (83). To improve the effectiveness of mass trapping of RPW in India, farmers are advised to use food bait and blends with aggregation pheromones at a rate of one trap per hectare (82). Typically, 1-2 traps per hectare are recommended to reduce the Economic Threshold Level (ETL) of RPW (1 %). In India, it was reported that the infestation reduced from 5 % to 0 % in one year and from 2.4 % to 0.2 % in 1.5 years (7) through these practices.

CRB, *O. rhinoceros*

In 1957, Cumber initiated research into chemical attractants for CRB but found limited results (84). The discovery of ethyl chrysanthemum, from which 'Chrislure' was synthesized, attracted significantly more CRB and was renamed 'Rhinolure', a cheaper alternative widely accessible in the market for farmers (85). The chromatography and antennal response to identifying volatile attractants from the African Rhinoceros Beetle species *Oryctes monoceros* (86). In a comparison study with ethyl chrysanthemum, E4 – MO was produced and tested as an attractant for *O. monoceros* in West Africa (Cote d'Ivoire). E4 - MO attracted male and female insects, but ethyl chrysanthemate did not attract CRB. They recognized E4-MO to be an aggregation pheromone. A third molecule, 4- 4-methyloctanoic acid, was later discovered to be the aggregation pheromone of the Fruit stalk Rhinoceros Beetle, *Oryctes elegans* Prell. In field studies in Indonesia, E4-MO proved to be 10 times more successful than 'Rhinolure' in catching both sexes (65). Adding freshly milled oil palm fruit bunches to E4-MO traps considerably increased its attraction (>60 %), suggesting that chemical cues from decaying organic debris can boost trapping efficiency (65). The effectiveness of pheromone traps is influenced by various factors, including trap design, placement, the frequency of checks, pheromone suppliers, the release rate of pheromones and the ecosystem being monitored (51). CPCRI has developed a new nano matrix for delivering CRB pheromone, which operates with reduced chemical quantities and demonstrates prolonged effectiveness in field applications (5). The widespread adoption of semiochemicals in coconut pest management faces several barriers, including high costs, which can be prohibitive for smallholder farmers and limited farmer awareness about their benefits and proper usage.

Sex pheromone

Pheromone gland extracts from one-day-old *O. arenosella* females were analyzed using GC-EAD and GC-MS. (Z, Z, Z)- 3,6,9 -tricosatriene (Z3Z6Z9-23Hy) was found to be the dominant sex pheromone compound. The male antennal response to female pheromone gland extract and synthetic Z3Z6Z9-23Hy was measured using GC-EAD. Results showed a positive reaction (0.13 mV and 0.14 mV, respectively) compared to the control (0.016 mV). Furthermore, identifying and synthesizing BHC pheromones (87) have facilitated the development of volatile-based mass-trapping, mating disruption and monitoring approaches. Pheromone traps have been widely adopted to monitor BHC population levels and guide management strategies in coconut plantations (87). The study found that 93.20% of the moths collected in pheromone-baited traps were males (87). Field testing found that utilizing 100 µg wing traps with Polyvinyl Chloride (PVC) vial dispensers dramatically increased pheromone loading and attracted male moths. The optimal pheromone dosage per lure was 0.1 mg (8). White cross -vane traps tied in the palm canopy at a density of 40-120 traps/ha resulted in the most successful population suppression by mass trapping. Notably, deploying pheromone traps alone can reduce BHC populations by 50-94 % (88), highlighting their potential as an effective management tool. These kairomones and sex pheromones serve as effective attractants for adult *O. arenosella* in field conditions. They could be incorporated into monitoring or management strategies based on volatiles, such as mating disruption or mass trapping (58). Many farmers remain unfamiliar with semiochemicals and may be reluctant to shift from traditional chemical pesticides, which they perceive as more effective and familiar. Additionally, the effectiveness of semiochemicals can be influenced by environmental conditions and pest resistance, reducing their reliability.

Allomone

RPW

Coconut petioles smeared with fresh toddy were deployed in coconut gardens to lure adults of RPWs. Applying a mixture of yeast and acetic acid to toddy-coated coconut logs increased trapping efficiency (61). To improve the trapping efficiency of the RPW, a combination of food lures, such as banana, sugarcane and coconut petioles and aggregation pheromones can be used. The kairomones released by host plants or food baits synergistically interact with the aggregation pheromones, thereby increasing RPW catch (80). Adding water to food baits in pheromone traps promotes fermentation, which releases VOCs that attract RPW adults (54).

BHC

Kairomones from the BHC larval gallery play an essential role in eliciting the behavioural response of larval parasitoid *Apanteles taragammae* towards BHC (89). The damaged coconut leaflet odours elicited a stronger antennal response are unknown (90). A hexane wash of the gallery and body of BHC elicited a positive reaction from efficient parasitoids such as *Goniozus nephantidis* Muesbeck and *Bracon brevicornis* Wesmael. GCMS analysis revealed the presence of dodecane, pentadecane, hexadecane, heptadecane, eicosane, and tricosane in the galleries. Females attracted to coconut leaf and larval frass volatiles exhibit considerably higher oviposition rates than controls. Chemicals found in leaf and frass, including Linalool (91.54%), Acetophenone (87.58%), and Limonene (80.65%) are promising for pest management. The behavioural test showed that when combining linalool with a sex pheromone at a 1:1 ratio and acetophenone at a 2:1 ratio, the male response was more significant than using the sex pheromone alone (91).

Coconut scale

Research was conducted to access the allelochemicals from preferred and non-preferred scale hosts. The collected VOCs of the healthy and non-infested host of the coconut scale were analyzed using GC-MS. Propanoic acid, also known as 2-methyl -2,2-dimethyl-1-(2-hydroxy-1-methylethyl) propyl ester, was found in the volatile profiles of feeding hosts such as coconut, mangosteen, areca and licuala. This chemical may help *A. destructor* find its hosts and feed on them in the infant stage (77).

Kairomone

RSW, A. rugioperculatus

α-Ocimene, α-Pinene, 3-Carene, trans-α-Ocimene, and (E)-hex -3-ene-2, 5-diol were five compounds that elicited the greatest attraction of *Encarsia guadeloupae* Viggiani towards RSW damaged plants. The synthetic blend of the above volatiles could be used as an attractant to enhance the population of *E. guadeloupae* to manage RSW under field conditions (92). Similar studies found that differences in the VOCs emitted from RSW-infested banana and coconut plants revealed higher emission of β-Caryophyllene, (E, Z)- 2,6-dimethyl-2,4,6-Octatriene, Humulene, α-Pinene, Farnesane, α- Copaene and β-cis-Ocimene from RSW infested banana plants that proved to be more attractive to *E. guadeloupae* (93).

Conclusion

Growing concern about human and environmental health has restricted certain broad-spectrum pesticides and strict residue rules. As a result, there is an urgent need for evolving sustainable novel solutions and target pest management strategies for specific insects. Semiochemical approaches have emerged as an essential component in IPM, helping with pest monitoring, forecasting and mass-trapping. Experts concur that semiochemicals-based approaches, particularly mass trapping and attract and kill approaches, are most effective in large-scale programs. Despite advances in chemical ecology, the commercial use of semiochemicals in coconut farms remains limited and must be popularized. Discovering host attractants and repellents and creating various implementation strategies with the scope of seeking semiochemicals employed more widely in farming systems for the upcoming years. Future research could focus on identifying highly specific semiochemicals for key coconut pests and optimizing advanced delivery methods like nanotechnology approaches for these compounds in coconut cultivation is essential. Additionally, evaluating the integration of semiochemicals-based tactics with other IPM strategies such as biological control or resistant plant varieties, may lead to more robust and sustainable pest management programs in coconut.

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Authors' contributions

KT and MA conceived the review article and drafted the main body of the manuscript. PSS, AS, VB, SV and SJ conducted the literature search. SV and PIG provided expert analysis and critically revised the manuscript. MM and MS contributed to the critical revision and improvement of the manuscript content. PAS formatted the entire manuscript. All authors approved the final version of the review article.

Compliance with ethical standards

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