Semiochemicals and Their Potential Use in Pest Management

Hamadttu Abdel Farag El-Shafie and
Jose Romeno Faleiro

Additional information is available at the end of the chapter

Abstract

This chapter gives an account on the general concept of insect semiochemicals, their definitions, classification, formulation, utilization in integrated pest management programs, and the shortcomings of their application. The different semiochemically based insect management techniques, such as mass trapping, mating disruption, and attract-and-kill, are highlighted. The chapter also summarizes a case study from 7-year research on semiochemicals of the invasive red palm weevil, *Rhynchophorus ferrugineus*.

Keywords: olfactometer, mating disruption, chemical ecology, pheromones, kairomones

1. Introduction

Chemical communication plays an important and essential role in the survival of insects, which enable them to appraise immediate environment through modification of their behavior. Semiochemicals are organic compounds used by insects to convey specific chemical messages that modify behavior or physiology [1]. The term semiochemical is derived from the Greek word "semeon" which means sign or signal. Insects use semiochemicals to locate mate, host, or food source, avoid competition, escape natural enemies, and overcome natural defense systems of their hosts. Semiochemicals have the advantage of being used to communicate message over relatively long distances compared with other insect means of communication such as touch. Semiochemicals have different molecular weights depending on carbon chain. They are biologically active at very low concentration in the environment, thus their chemical characterization is complicated.

Expensive equipment items are needed for extraction and chemical characterization of semiochemicals. These equipment items include solid-phase microextraction (SPME), gas chromatography-electroantennography (GC-EAG), gas chromatography-mass spectrometry (GC-MS), and nuclear magnetic resonance (NMR) [2]. For the development of new synthetic pheromone blend, a lot of work on electrophysiological and behavioral bioassay is required [3].

Semiochemicals are species-specific and harmless to the environment. These advantages over conventional insect pest control agents make semiochemicals promising tools for the management of agricultural pests particularly under organic cropping systems.

2. Classification of semiochemicals

Semiochemicals are classified based on their effect or function and this should be taken into account because the same molecule could act as a pheromone for one insect species and as a kairomone or allomone for another species. Semiochemicals are divided into two broad groups: pheromones that mediate interactions among individuals of the same species (intraspecific reactions) and allelochemicals that mediate interactions among individuals of different species (interspecific interactions). According to the behavioral response, pheromones are further subdivided into primer pheromones that have long-term physiological changes and releaser pheromones that elicit short-term or immediate behavioral response. Allelochemicals are divided into kairomones that mediate interactions favoring the recipient, allomones, on the other hand, favor the emitter. Synomones favoring both the emitter and the recipient, and apneumones, which are substances, produced by nonliving material that elicit behavioral response favorable to the receiving organism but harmful to a second organism found on the nonliving material. Schematic diagram showing the classification of semiochemicals is shown in **Figure 1**.

2.1. Insect pheromones

Karlson and Lüscher [4] first proposed the term pheromone to describe chemical signals that mediate intraspecific interactions. The sex pheromone of the silkworm moth, *Bombyx mori* was the first pheromone to be chemically identified in 1959 and is considered as the most important semiochemical used in pest management. Other pheromones include aggregation pheromone, which are produced by males and attract both sexes of conspecific individuals. The sex pheromone of moths is the most studied and widely used in insect pest management than other pheromones [3]. One-day-old female moth emits the sex pheromone usually at a rate of a few tens of picogram per second at a certain time of the day or night. It has a characteristic behavior of raising the abdomen and exposing the pheromone glands at the end of the abdomen, this behavior is termed as calling posture [3]. Male moths, on the other hand, synchronize their daily activity to calling females for mating to be successful. The males respond to pheromone by flying upwind in the plume from 10 to 100 m downwind to locate the source [3]. Insect pheromones diffuse from their source in the form of strands of odor that drift downwind and become stretched, twisted, and ripped apart into substrands, which interspersed with pockets of clean air to form odor plume that produce the sustained upwind flight or what is termed as attraction [5, 6].

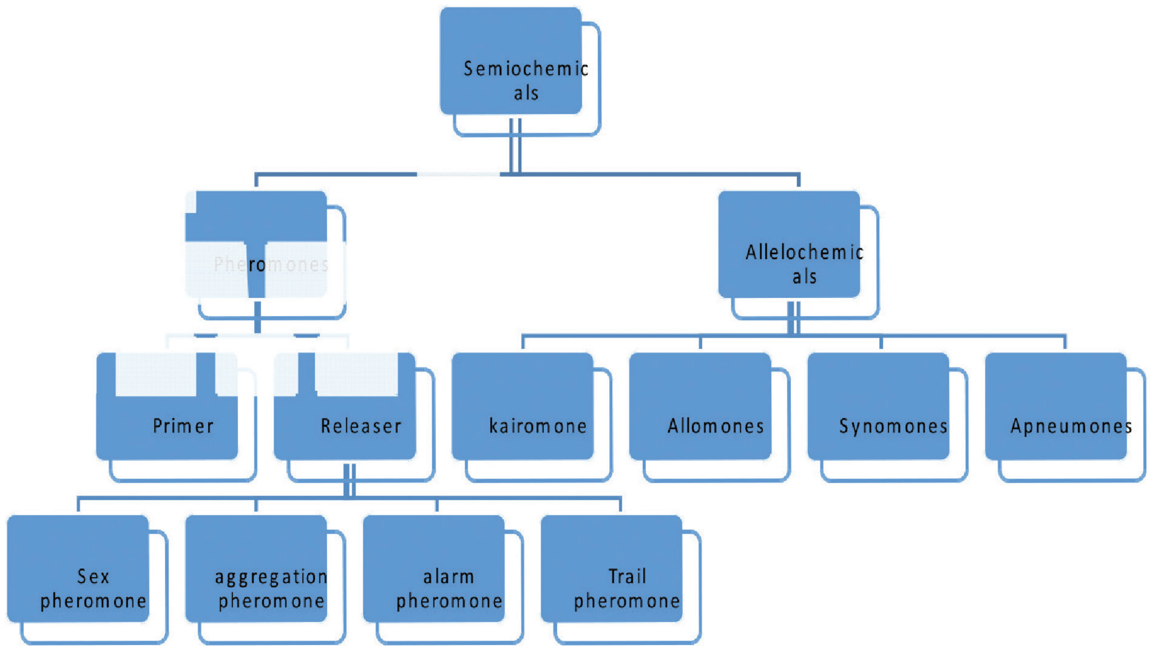

Figure 1. Classification of semiochemicals based on their effect and role in specific interactions.

2.2. Insect parasitoid kairomones

Semiochemicals play an important role in host-parasitoid relationship, which was categorized by [7] into three stages: habitat-location, host-location and host-acceptance, and oviposition. These semiochemicals included but not limited to aldehydes, alcohols, sulfur-containing compounds, esters, terpenes, alkanes, heterocyclic aromatic compounds, proteins, amino acids, triglycerides, and salts. He stated that 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, semiochemicals are predominantly from the 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 [7]. The internal kairomones represented by amino acids and salts in the hemolymph, which 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.

3. Identification and behavioral characterization of semiochemicals

Identifying the range of volatiles that insects can detect in their environment is an important step toward understanding the role of olfaction in modulating insect behavior [8]. 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 behavioral response of the insect to the active product. If the organ that produces the semiochemical is known, for example, the exocrine gland or the gut of the insect, it can be extracted and identified. However, nonrelevant compounds can also be extracted, which complicate the identification process. Accordingly, headspace collection is preferred instead [2] where a charcoal-filtered air is passed over the insect or its organ in an isolated aeration chamber and the odor-laden air is withdrawn by vacuum for analysis [8]. The air containing a mixture of volatiles can be analyzed *per se* or after being absorbed by super Q using columns. In the 1950s, it has been discovered that a measurable voltage arised between the tip and base of the insect antenna when exposed to odors of biological significance for the insect. This antennal response to different odors is known as electroantennogram or EAG [9]. This voltage is thought to represent the summed potentials of multiple responding olfactory neurons within the antenna, and the amplitude of the voltage roughly corresponds to an insect's sensitivity to a particular compound. The EAG has been widely used in entomology for pheromones' identification. 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. This analytical procedure allows for rapid and accurate identification of insect odors. It is widely used to discover and identify semiochemicals like insect pheromones and repellents [8, 10]. The apparatus consists of injector (heated chamber), the column (10–100 m long, 1 mm wide) lined with a semisolid wax or polymer, flame ionization detector, insect antennal preparation, and a monitor to display the voltage output of the detector and the insect antenna (voltage on the Y-axis against time on the X-axis). Retention time and peak of each molecule give the identity and amount of the compound in the mixture, respectively. The FID output can be used to confirm the presence, identity, and quantity of compounds exposed to the antenna while the antennal (EAD) output indicates the presence/absence of olfactory sensitivity to eluting compounds and provides a relative measure of the intensity of olfactory stimulation. The FID peaks of the test compounds can be compared with retention times of those of commercially available versions of the same compounds injected into the GC. Identifications can be confirmed by re-analyzing the extract with a coupled gas chromatography-mass spectrometer (GC-MS) using the same column and GC operating parameters as used in the GC-EAD analysis. Testing the behavioral activity of EAD-active volatiles is an important and complementary step in the identification of semiochemicals that modify insect behavior. This behavioral bioassay test can be carried out using wind tunnel or an olfactometer [11, 12].

4. Interaction of insects and plants semiochemicals

Insects live in an environment with many volatile compounds including insect herbivore, host plant, and insect carnivore semiochemicals. These volatile chemicals interact with each other and finally modify the behavior and the physiology of insect pest species. Some insects sequester or acquire host plant compounds and use them as sex pheromone or sex pheromone precursors [13]. Many butterflies, moths, beetles, grasshopper, and aphids used pyrrolizidine alkaloids from their host plants as strong feeding deterrents against their natural enemies or predators [14]. It has been shown that the oil palm *Elaeis guineensis*, the host plant of the

African palm weevil *Rhynchophorus phoenicis* produce a mixture of volatile esters of which the ethyl acetate induces male weevils to release the aggregation pheromone E-6-methyl-2-hepten-4-ol or rhyncophorol [15]. The males of orchid bees collect a mixture of terpenoids from the orchids and use them as aggregation pheromone to induce the formation of leks or the sites where males compete for females [16].

5. Potential use of semiochemicals in insect pest management

Semiochemicals have been used for insect pest management more than 100 years ago [2]. Insect sex pheromones are the semiochemicals that are widely used for the management of insect pest particularly members of the order Lepidoptera. Aggregation pheromones from the order Coleoptera are also used for the management of agricultural insect pests of economic importance. Several serious agricultural pests including the carob moth *Ectomyelois ceratoniae*, the armyworm *Spodoptera frugiperda*, tomato leaf miner *Tuta absoluta*, fruit flies *Bactrocera* sp., mountain pine beetle (MPB) *Dendroctonus ponderosae*, Asian citrus psyllid *Diaphorina citri*, and the red palm weevil (RPW) *Rhynchophorus ferrugineus* have been successfully managed by using semiochemicals.

Semiochemicals are considered safe and environmentally friendly molecules due to their natural origin, low persistency in the environment, and species specificity, which attribute much to their harmless effect on nontarget organisms [17]. However, there are some difficulties in the practical applications of semiochemicals in pest management, and due to these challenges Semiochemically-based pest methods are still at the beginning [2]. Baker [3] mentioned the reasons that promoted or hindered the adoption of pheromones in the management programs of insect species as follows:

a. The biological differences in the mate-finding behavior of different species.

b. The chemistries of the pheromones used.

c. The successful engineering of the controlled-release dispenser and the use of proper trap design

d. The different political, economic, and use-pattern in different countries particularly the regulation of pheromones' application.

6. Semiochemical formulations

Strong plumes of the correct blend of pheromones that create the above-threshold plume strands for downwind of the pheromone source are the key points to the optimal use of pheromones in integrated insect pest management programs. To achieve this, a controlled-release system of pheromone dispenser that mimics the natural pheromone release by insect pest is required [3]. In addition, optimization of trap density, design, and trap position is essential to achieve trap efficiency.

Mafra-Neto et al. [18] listed the shortcomings in semiochemical formulations as follows:

a. High cost of semiochemicals in terms of method of deployment in the field compared to conventional synthetic pesticides. Most semiochemicals used in insect pest management are formulated in the form of devices which require manual application.

b. The physical limitations such as instability, volatility, and sensitivity of the active ingredient of the semiochemicals to environmental factors like temperature and light.

c. Inconsistency of semiochemical product to maintain release rate and short-field longevity.

d. Mechanism of behavior manipulation in some techniques in which the semiochemical is used (e.g., mating disruption formulation that acts by camouflage requires large quantity of pheromone to be deployed which means more application cost).

For the above-mentioned reason, ISCA technologies developed an innovative semiochemical application technique for agricultural and forest insect pests. The technique is called specialized pheromone and lure application technology (SPLAT®). It is an amorphous, flowable, and controlled-release emulsion, with chemical and physical properties that may be adjusted by small changes in composition in processing or application method. A shear-thinning thixotropic, non-Newtonian fluid enters a liquid state by agitation, but quickly solidifies when agitation is stopped. These physical characteristics give the formulation flexibility in application. SPLAT® can provide a continuous controlled-release of semiochemicals for a period ranging from 2 weeks up to 6 months [18].

Semiochemicals are utilized for the management of insect pests through the following tactics:

a. Detection of invasive species and in delimiting surveys.

b. Monitoring the populations of endemic species to synchronized the timing of insecticide treatments

c. Evaluation of the effectiveness of pest management tactics through post-application assessment.

d. Improvement of old method of insect counts used for decision-making.

e. Increasing the effectiveness of biological control by increasing the predation/parasitism rates of predators and parasitoids. Kairomones could be applied to plants to increase the rate of parasitization through increasing the search rate of *Trichogramma* sp. [19].

f. Reduction of pest population through mating disruption, attract and kill, mass trapping, and repellency techniques.

7. Semiochemical-based pest control techniques

7.1. Attract and kill (A&K)

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), hence the technique is termed attract and kill, attract and infect, and attract and sterilize, respectively. 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. For more information on this technique regarding the fundamental requirements for both the attractant and the killing agent, please see Mafra-Neto et al. [18].

7.2. Mating disruption

The technique is most commonly used in semiochemical-based pest management. It manipulates insect behavior 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 [18]. Mating disruption using synthetic pheromones or parapheromones does not completely shut off mating, but the delay in females mating may reduce their fecundity by approximately 50% [3]. 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 [18]. The mating system of some insects involves the transfer of certain peptides that trigger the egg laying behavior in the females. 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 [18]. 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.

7.3. Mass trapping

It is a pheromone technique commonly used for direct insect population suppression. The technique is defined as the deployment of sufficient high density of pheromone traps that eliminate enough adults from the population and thus reduce subsequent larval damage [3]. Pheromones for monitoring are usually used at low density and the trapped insects have no effect on reduction of the population [20]. 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. The technique is effective with insects having relatively low population, live a long time before egg-laying, lay small number of eggs, and the emerging larvae cause considerable damage [21].

7.4. Repellents

A repellent is defined as a substance that deters or inhibits insects from finding, feeding on, or ovipositing on an attractive host substrate [18]. Several semiochemicals with repellent effect are available for the management of agricultural and forest pests. However, their practical application is limited due to the availability of cheap and effective pest control alternatives, lack of adequate formulations for delivery, and regulatory obstacles including registration [22].The repellent "verbenone" is now commercially available for the management of mountain pine beetle (MPB), *Dendroctonus ponderosae*. The repellents can be used alone or in combination with attractants for the management of insect pests as part of a push-pull strategy. Cook et al. [23] defined the push-pull strategy as the use of semiochemicals to make a protected resource an attractive or unsuitable for the pests (push) while luring them to an attractive source (pull) where the pests can be removed. Compared to other semiochemically based pest management techniques such as mating disruption or attract-and-kill, push-pull strategy requires more understanding of the chemical ecology of the insect pests [23].

8. A case study of the red palm weevil in date palm plantation

The red palm weevil (RPW), *Rhynchophorus ferrugineus* (Coleoptera: *Curculionidae*), is an invasive and destructive insect pest of date palm worldwide. RPW was first reported as a pest of coconut palm in India and since the 1980s, it has invaded many countries around the globe. The weevil is a relatively large insect exhibiting different color morphs and sexual dimorphism where the male can be easily distinguished by the presence of dense hairs on the rostrum which are absent in the female. The weevil is extremely difficult to manage because all the life stages are concealed inside the date palm tissues and are difficult to detect at an early stage of damage. Several tactics including preventive and curative measures are adopted to manage the weevil in date palm plantations [24]. However, RPW is currently managed in date palm groves through semiochemically based integrated management using male-produced aggregation pheromone or (4-methyl-5-nonanol) for both monitoring and mass trapping of adult weevils [25]. This pheromone was first identified and synthesized in the early 1990s and has since proven a valuable tool for the management of RPW [26]. The aggregation pheromone acts synergistically with 4-methyl-5-nonanone (ketone) and is more attractive to RPW when combined with kairomones or volatiles emitted from the host to increase the efficiency of the blend [25]. The RPW pheromone (Ferrolure +) is commercially available (a mixture of 4-methyl-5-nonanol and 4-methyl-5-nonanone with a ratio of 9:1) released at 3–10 mg/day. The addition of ethyl acetate (released at 200–400 mg/day), fermenting mixture of dates and water increases trapping efficiency. The pheromone/food-based trapping system is considered as an environmentally friendly approach compared to the use of insecticides, which is currently being applied for the control of RPW [27]. Ferrugineol is attractive to both sexes; however, several researchers reported that traps baited with this attractant tend to capture significantly more females than males, usually with a ratio of two females to one male [24, 28, 29]. In addition, the captured weevils were found to be young, gravid, and fertile, indicating significant impact of trapping on the population reduction of the weevil in a given locality [30, 31]. The advantages of semiochemicals over other methods of pest control are that they are naturally occurring substances with species-specific character. Semiochemicals, a major component of IPM strategy for the management of red palm weevil in date palm [32], are environmentally friendly and have no adverse effects on natural enemies and pollinators in the agro-ecosystem. The aggregated nature of RPW distribution in the field, the long-life cycle, adult longevity, reliance on aggregation pheromone and host kairomone, and the relatively low population make the use of semiochemicals ideal for the management of this notorious pest [33]. To have an efficient semiochemical-based management program for RPW, a highly optimized pheromone product is needed in terms of attraction to lure the weevil directly to the trap (point source). The weevil must successfully locate the trap, arrested and enter inside; otherwise, it will infest the palm, which should be avoided when using traps. The trap should be more attractive and arresting for the weevils than the natural kairomone emitted by the date palm in the field. Optimizing the RPW trapping system requires better understanding of semiochemical ecology of the weevil in date palm plantation. Accordingly, the authors conducted a series of laboratory and field experiments that expand for 7 years to understand the chemical ecology and semiochemicals of red palm weevil in the date palm plantations in order to optimize trapping efficiency for an effective semiochemically based integrated management of this notorious pest. A summary of the results of these experiments is given in the following paragraphs.

8.1. Research methodology

All laboratory experiments were conducted in the Date Palm Research Center of Excellence (latitude 25.16′6.9780″N, longitude 49.42′27.2772″E, and altitude 153 m), King Faisal University, Kingdom of Saudi Arabia. The field experiments were conducted in highly infested date palm groves selected based on data of trap catches obtained from the Directorate of Agriculture, Al-Ahsa, Ministry of Agriculture, and Kingdom of Saudi Arabia. Weevils used in olfactometer assays were obtained from a colony of RPW, which was established in the laboratory on bolts of the popular date palm cultivar "Khalas" that represent more than 85% of the cultivated date palms in Al-Ahsa oasis where the study has been carried out. To obtain virgin weevils, pupae were collected from the reared colony, and each pupa was kept separately in 20-ml-plastic jar with perforated lid. The jars were then kept in an incubator at a temperature of 30°C and 70% RH until adult eclosion. Emerged adult weevils were fed ad libitum on sugar cane for at least 3 days before being used for the different experiments.

8.1.1. Olfactometer bioassays

Olfactometers are used to gauge the odor detection threshold of substances. A four arm-choice olfactometer®, a custom-made by Analytical Research Systems, Inc., Florida (ARS Inc., Florida) (www.ars-fla.com/mainpages/Bio-Assay/4 & 6-choice.htm) was used to study the weevils' preference to different lures (**Figures 2–4**). This olfactometer was connected to a pump that maintained a constant flow of pure air through the four arms while at the same

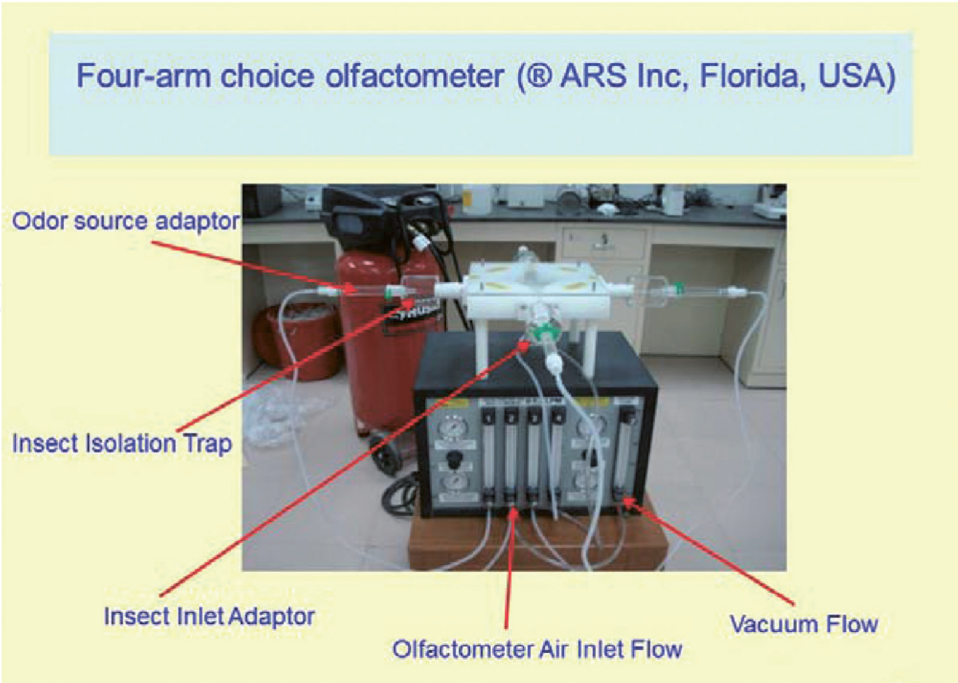

Figure 2. The layout of the four-arm choice olfactometer is shown. It consists of three units: a pump to provide purified air, clean air delivery system (vacuum), and odor exposure arena with polyethylene body and removable lid made of plexiglas.

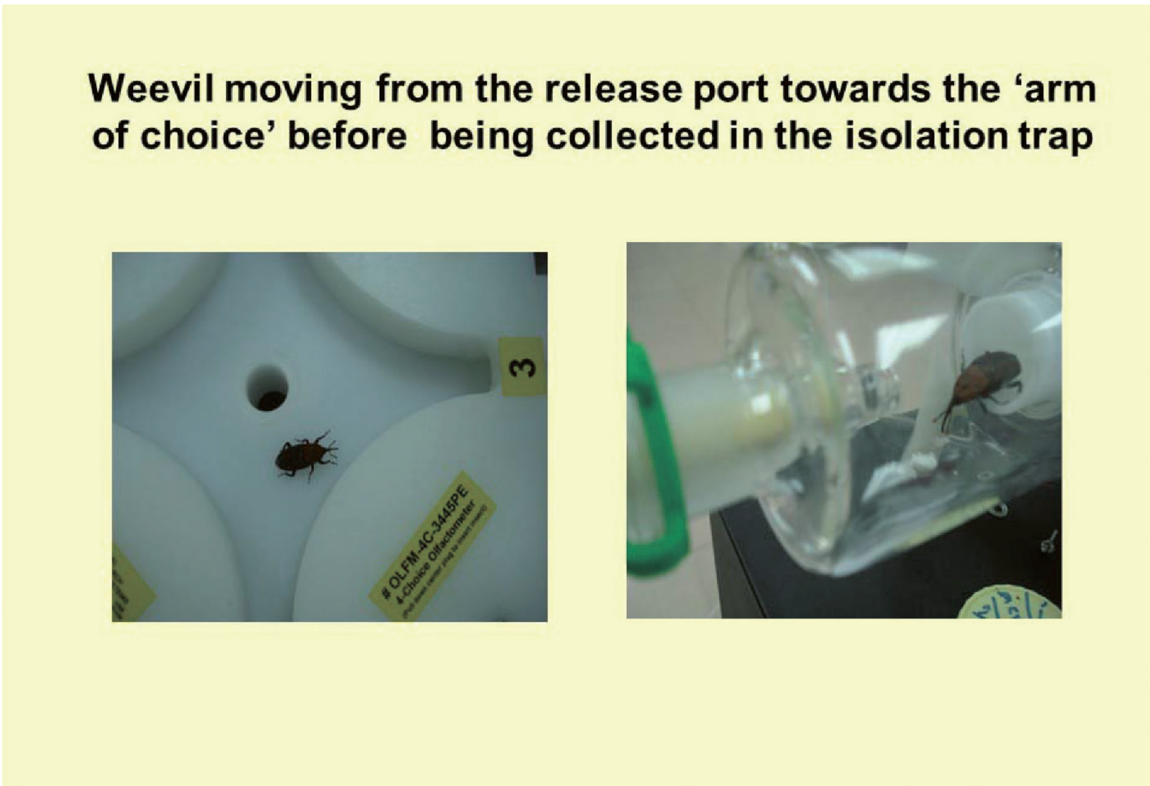

Figure 3. Dorsal view of the olfactometer showing insect inlet adaptor and isolation trap. An adult weevil moving upwind responding to odor source (*left*) before ending up in the insect isolation trap (*right*).

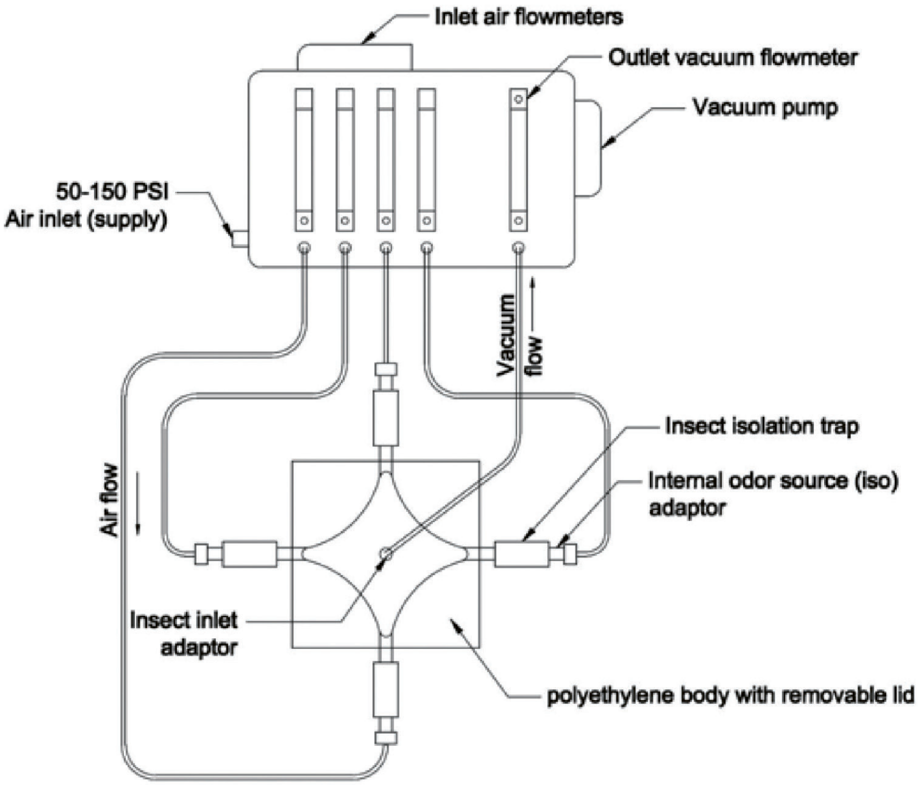

Figure 4. Schematic diagram of a four-arm olfactometer illustrating how it works. The olfactometer was connected to a pump that maintained a constant flow of pure air through the four arms while at the same time vacuuming out the odors emitted by the treatments through central suction. Four-flow meters controlled airflow in the olfactometer. Each of the four arms of olfactometer is provided with an odor source to be bioassayed, thus providing four odor fields for the test weevils to make a choice. Weevil directional preference to one of the four arms is used as an indicator to assess its behavioral response to that odor.

time vacuuming out through central suction the odors emitted by the treatments. Four-flow meters control airflow in the olfactometer. Each of the four arms of olfactometer is provided with an odor source to be bioassayed, thus providing four odor fields for the test weevils to make a choice. Weevil directional preference to one of the four arms is used as an indicator to assess its behavioral response to that odor. The apparatus is manipulated in such a way that other factors, which might affect the weevil response to the odor, are controlled. More details on the functioning of the olfactometer are given in Section 8.3 of this chapter. The olfactometer was calibrated before carrying out the experiments according to the specifications shown in **Table 1**.

8.2. Optimizing components of pheromone-baited traps

Several assays were carried out to evaluate the response of both male and female RPW adults to the aggregation pheromone (Ferrolure™) (El-Shafie and Faleiro, unpublished data). The test insects were (i) newly emerged unmated/mated insects and (ii) 1-month-old mated insects. Newly emerged insects were tested individually (20 replicates) while the 1-month-old adults were tested in batches of five weevils (10 replicates). The internal odor source (IOS) adapter of the olfactometer was moved from one arm to another sequentially, so that each arm of the

Inlet/outlet pressure and air flow rate	Test calibration
1. Olfactometer pressure (10–20 PSI)	15 PSI
2. Source inlet pressure (50–150 PSI)	60 PSI
3. Olfactometer vacuum: center suction (−5 to −22″Hg)	−10″Hg
4. Vacuum pump pressure (60 + PSI)	+60 PSI
5. Olfactometer air inlet flow (0–1.3 LPM)	0.9 LPM

ARS Inc, Florida, USA.
PSI = pounds/square inch; ″Hg = inch mercury; LPM = liters per minute.

Table 1. Calibration of the olfactometer® to study the response of the red palm weevil (RPW) to different RPW pheromone lures.

olfactometer had the same number of replicates thereby eliminating bias of the instrument and environment if any. Besides the commercial pheromone, the internal odor source of the instrument containing the lure was charged with 1 ml fermented date solution dispensed in a perforated tube. A 5-min period was allowed for the test insects to move toward the arms from the insect release tray (IRT). Weevils collected in the insect isolation trap (IIT) at the end of 5 min were recorded.

The results presented in **Figure 5** reveal significant and high attraction (>50%) to the aggregation pheromone in newly emerged unmated male and female weevils. Upon mating both newly emerged male and female weevils were significantly attracted to the pheromone but at a reduced (~30%) rate as compared to newly emerged unmated (virgins) individuals. With age (1 month old), the attraction to the pheromone reduced still further with only 14% of the female weevils responding significantly to the pheromone, whereas 1-month-old male

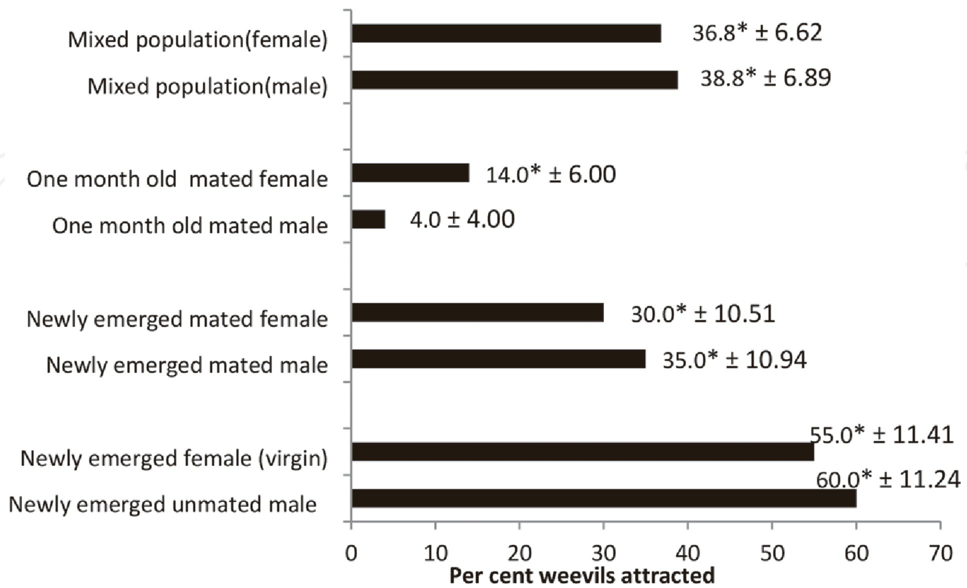

Figure 5. Response of *R. ferrugineus* to the aggregation pheromone in choice olfactometer assays (*t*-test; *significant at p = 0.05).

weevil did not show significant attraction to the pheromone. In general, around 35% of the test insects (male and females) were attracted to the pheromone. The RPW uses the aggregation pheromone (ferrugineol) to recruit conspecific mates over long distance to colonize its host. This biological characteristic has been extensively utilized to manage this weevil through monitoring and mass trapping. Our results revealed that the response of RPW (males and females) to aggregation pheromone increased with mating as supported by the finding of Poorjavad et al. [34] who studied the effect of different doses of the aggregation pheromone on the diurnal response of virgin and mated males and females RPW under laboratory conditions using a two-choice pitfall static olfactometer. The authors concluded that in both sexes, the response to ferrugineol increased with mating. Mated females showed strong response to ferrugineol than unmated ones, due to the searching behavior of the former for egg laying sites.

Weissling et al. [35] stated that the optimal attraction of weevil to trap is affected by the proportional changes in volatile chemicals from fermentation overtime. These volatile chemicals or kairomones, as determined by GC-MS, included palm esters, ethyl acetate, ethyl propionate, ethyl butyrate, and ethyl isobutyrate [36]. Kumar et al. [37] tested different pheromone lures in India and reported differences in their efficiencies. This discrepancy could be attributed to difference in environmental conditions between India and Saudi Arabia where the present investigation was carried out. In this context, Faleiro and Chellapan [38] reported a difference in longevity of the lures in different seasons (winter and summer). They stated that the release of pheromone into the environment is faster in summer than in winter and that was attributed to higher temperature and day light. Thus, they recommended putting traps under shade conditions to sustain the efficiency of the trapping system. The fact that only 35% of the test weevil (males and females) responded to the aggregation pheromone, which is supported by El-Sayed et al. [27], require that the remaining population in the field have to be managed through other IPM tactics.

8.3. Determining the extent of attraction of weevils to date palm volatiles

Faleiro et al. [12] studied the mechanisms of resistance against RPW in seven major date palm cultivars of the Al-Ahsa oasis in Saudi Arabia viz. Khalas, Sheshi, Reziz, Khasab, Hatmi, Shahal and Gaar by determining the extent of attraction of female RPW adults to fresh palm volatiles emitted from date palm frond tissue through four-arm choice olfactometer assays. In each of the inlet odor source (IOS) adapters of the olfactometer, freshly cut palm petiole pieces (5 × 1 × 1 cm) of a single cultivar were placed. Two experiments were carried out wherein four cultivars were tested at a time with Khalas as the control treatment in both the experiments. Fifteen-day-old field collected gravid adult female weevils were used in the assays. Five female weevils were placed in the insect release device of the olfactometer. After 5 min, the number of adult female weevils collected in the insect isolation trap (IIT) was noted. Each experiment was replicated eight times. At the end of each assay (replication), palm tissue pieces and test insects used in the assay were discarded. New palm tissue pieces and test insects were used for every replication (assay). The IOS was moved sequentially to the next arm of the olfactometer at the end of each test replication so that every treatment was at the same arm of the olfactometer twice during each trial.

This was done to eliminate bias if any in the instrument and environment. Results revealed that the popular date palm cultivar Khalas had the least antixenotic effect on female RPW adults where a high degree of attraction to palm tissue volatiles was recorded which was statistically similar to the cultivars Reziz, Sheshi, and Hatmi. The cultivars Khasab, Shahal, and Gaar exhibited high degree of nonpreference (antixenosis) (**Figure 6**). Identifying the chemical components of tissue volatiles that trigger antixenosis in date palm to RPW will pave the way for future studies on chemical ecology of RPW and its interactions with date palm as a main host.

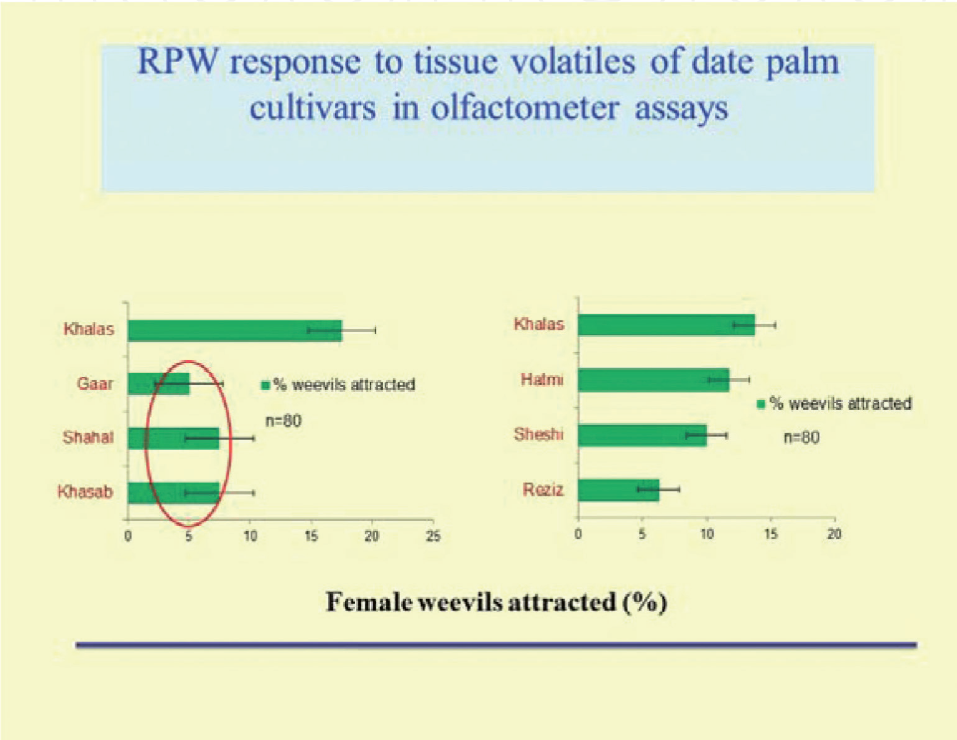

Figure 6. Red palm weevil response to tissue volatiles of date palm cultivars in olfactometer assays.

8.4. Testing the efficacy of Hook™ RPW versus food-baited pheromone traps

Food-baited pheromone traps (FBPTs) have been used to manage the red palm weevil in date plantations through monitoring or mass trapping techniques for population reduction. The FBPTs are simply made of plastic buckets baited with ferrugineol and fermenting dates as sources of kairomone **Figures 7** and **8**). The main problem with FBPTs is that they require frequent service (replacement of food bait and water) which makes their utilization over large area laborious and expensive. ISCA technologies developed Hook RPW is an attract-and-kill formulation that combines the aggregation pheromone and the insecticide cypermethrin. The formulation does not require service once deployed in the field, thus it can drastically reduce application cost particularly in area-wide RPW integrated management.

Figure 7. The standard RPW bucket trap showing the main components.

Figure 8. A marked RPW male walking toward the food-baited pheromone trap.

El-Shafie et al. [39] tested the efficacy of Hook™ RPW in an infested date plantation in Eastern province of Saudi Arabia. The product was applied in hundred 3 g dollops at an application rate of 250 dollops per ha. The area of treated plot was 0.4 ha containing ca. 60 date palms of the popular variety "Khalas." The number of weevils attracted to source point and killed was compared with the catches of the conventional FBPTs commonly deployed by the Directorate of Agriculture to manage RPW in date palm plantations. The data of weevils captured per week in the treatment plots was converted to number of RPW caught per ha per week to compensate for the discrepancy in trap density between the two trapping methods. Results revealed no significant difference between Hook RPW and FBPTs indicating that SPLAT formulation can be successfully used as a potent component in the integrated management of RPW. In a separate trial concerning bait-lure synergy, Hook RPW sustained the same level of attraction to PRW regardless of the presence or absence of food bait [39]. SPLAT for RPW proved to maintain field longevity and efficacy for 3 months under the dry summer conditions of Saudi Arabia.

A 10-fold increase in pheromone trap number in Al-Hasa date palm oasis during the period from 2007 to 2012 in Saudi Arabia decreased the RPW infestation in an area of 1104 ha by 86%. Likewise, the application of insecticides was reduced by 91% and the felling and eradication of infested date palm trees dropped by 89% [40]. Similar stories of successful management of RPW using semiochemicals in the Gulf and the Middle East are documented [28, 41]. The research on semiochemical repellents of RPW has been initiated and Guarino et al. [42] identified α-pinene and methyl salicylate for being potential repellents for RPW. This could open an avenue for the future use of push-pull strategy for integrated management of red palm weevil.

9. Conclusions

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. Mated RPW females responded more to the aggregation pheromone than virgin females indicating that an egg-laying stimulus may be responsible for deriving these females to the aggregation pheromone. Large number of RPW adult weevils fly to traps located near to their colony to nearby traps and increasing distance to trap from infestation spot increase the probability weevil will not find the trap. This behavioral response of RPW to aggregation pheromone should be considered when specifying trap density per ha for mass trapping. Some date palm cultivars exhibited different kinds of resistances to RPW the mechanisms of which vary; however, antixenosis or egg-laying nonpreference is important. Future research on semiochemicals for insect pest management should focus on innovative formulation for field deployment as well as on optimization of controlled-release technologies and trapping efficiency. More research on the chemical ecology of target insect pest is of paramount importance for development of semiochemically based insect pest management programs.

Author details

Hamadttu Abdel Farag El-Shafie[1]* and Jose Romeno Faleiro[2]

*Address all correspondence to: elshafie62@yahoo.com

1 Date Palm Research Center of Excellence, King Faisal University, Al Ahsa, Kingdom of Saudi Arabia

2 Food and Agriculture Organization of the UN, Date Palm Research Center, Ministry of Agriculture, Al-Ahsa, Kingdom of Saudi Arabia

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