

Pheromones in the integrated management of Arecaceae-defoliating pests. A review

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Introduction. The cultivation of Arecaceae is subject to infestation by defoliating insects, which requires efficient monitoring methods. Semiochemicals, mainly sex pheromones, are now widely employed. The present literature review aims to list the main defoliating pest species of Arecaceae and their associated semiochemicals to identify all research efforts on the use of pheromones to control these pests, and to discuss further research directions for their monitoring and control in Arecaceae cultivation.

Literature. The main defoliating insects are Lepidoptera, Coleoptera and Orthoptera. Pheromone application for their control is an established practice for eight genera of Lepidoptera, with published studies on the use of synthetic sex pheromones employed mainly in Southeast and South Asia. These pheromones mainly include saturated and unsaturated esters, alcohols, aldehydes, terpenoids and polyunsaturated hydrocarbons. The generalist defoliator insects' pheromones are also discussed as well as gregarious grasshoppers and the need for continuous research on developing and using pheromones in producing regions.

Conclusions. Pheromones are important tools for monitoring and controlling Arecaceae pests; however, it is important to study species that have not yet been researched. For better efficiency in their use, it is necessary to improve and adapt field techniques to environmental conditions and to develop monitoring and control technologies for all Arecaceae-producing regions.

Keywords. Behavioural manipulation, chemical ecology, semiochemicals, *Cocos nucifera*, *Elaeis guineensis*, *Phoenix dactylifera*.

Phéromones dans la gestion intégrée des ravageurs défoliateurs d'Arecaceae (synthèse bibliographique)

Introduction. La culture des Arecaceae est sujette à une infestation par des insectes défoliateurs, ce qui nécessite des méthodes de surveillance efficaces. Les substances sémiologiques, principalement les phéromones sexuelles, sont désormais largement utilisées. Cette revue de littérature vise à répertorier les principales espèces de ravageurs défoliateurs des Arecaceae et leurs substances sémiologiques associées, afin d'identifier l'ensemble des recherches sur l'utilisation des phéromones pour contrôler ces ravageurs et de discuter des orientations futures pour leur surveillance et leur contrôle dans la culture des Arecaceae.

Littérature. Les principaux insectes défoliateurs sont les lépidoptères, les coléoptères et les orthoptères. L'application de phéromones pour leur contrôle est une pratique établie pour huit genres de Lepidoptera, avec des études publiées sur l'utilisation de phéromones sexuelles synthétiques utilisées principalement en Asie du Sud-Est et du Sud. Ces phéromones comprennent principalement les esters saturés et insaturés, les alcools, les aldéhydes, les terpénoïdes et les hydrocarbures polyinsaturés. Les phéromones des insectes défoliateurs généralistes sont également abordées, de même que les sauterelles grégaires et la nécessité d'une recherche continue sur le développement et l'utilisation des phéromones dans les régions productrices.

Conclusions. Les phéromones sont des outils importants pour la surveillance et le contrôle des ravageurs d'Arecaceae. Cependant, il est important d'étudier les espèces qui n'ont pas encore fait l'objet de recherche. Pour une meilleure efficacité de leur utilisation, il est nécessaire d'améliorer et d'adapter les techniques de terrain aux conditions environnementales et de développer des technologies de suivi et de contrôle pour toutes les régions productrices d'Arecaceae.

Mots-clés. Manipulation comportementale, écologie chimique, substance sémi chimique, *Cocos nucifera*, *Elaeis guineensis*, *Phoenix dactylifera*.

1. INTRODUCTION

The Arecaceae family has a wide geographic distribution in tropical regions, including species commonly known as palm trees. Arecaceae display great productivity and a variety of uses, being of great nutritional, medicinal, sociocultural and economic importance (Zambrana et al., 2007; Souza & Lima, 2019). Among the factors limiting their cultivation is the incidence of insect pests in cultivation regions, and these pests cause significant losses throughout cultivation, delays in vegetative development, loss of productivity and significant economic losses, especially in monoculture systems (Ferreira, 2008; Gitau et al., 2009). Insect pests associated with Arecaceae cause injuries to various parts of the plant; the feeding behavior of these pests makes it possible to classify them as defoliators, borers, suckers and moths, in addition to the presence of mites of agricultural relevance (Ferreira & Lins, 2006). Defoliators generally cause injuries to the leaves, reducing the photosynthetic area, and can even cause total defoliation, delaying plant development, reducing production and causing premature fruit fall. This type of pest is often associated with Arecaceae of agricultural importance, such as *Cocos nucifera* L., *Elaeis guineensis* Jacq., *Euterpe oleracea* Mart. and *Phoenix dactylifera* L., in addition to the many ornamental palm trees and species present in native vegetation (Mohan et al., 2010; Brandão et al., 2017; Ghnimi et al., 2017; Almeida et al., 2019).

The adoption of pest management programs in Arecaceae crops advocates the development of sustainable techniques for surveying, monitoring and controlling insect populations in the field (Faleiro et al., 2016).

Semiochemicals play an essential role in these crops given the specificity of these substances. The use of pheromones in these crops is carried out through traps to monitor and control insect pests, thereby reducing their populations and reproductive success (Ceruti, 2007).

The present literature review aims to list the main defoliating pest species of Arecaceae and their associated semiochemicals to identify all research efforts on the use of pheromones to control these pests, and to discuss further research directions for their monitoring and control in Arecaceae cultivation.

2. LITERATURE

2.1. Methods

This work was carried out using a qualitative approach with the objective of an exploratory study and a bibliographic review. To list the pests described as defoliating Arecaceae, surveys by Ferreira et al. (1998), Howard et al. (2001), Martínez et al. (2009) and Oliveira et al. (2018b) were considered. The geographic distribution of these pests was indicated based on consultations on the CABI and GBIF Secretariat platforms.

To identify the research efforts conducted in the field of chemical ecology of Arecaceae defoliators, indexes in the Web of Science, Scopus and Scielo databases were used, with descriptors aligned with the objective of the work. The following descriptors and combinations using Boolean operators were used: *Acharia* OR *Adoretus* OR *Agonoxena* OR *Alurnus* OR *Amathusia* OR *Antaeotricha* OR *Artona* OR *Atta* OR *Aularches* OR *Automeris* OR *Brassolis* OR *Brontispa* OR *Cephaloleia* OR *Coelaenomenodera* OR *Contheyla* OR *Coraliomela* OR *Darna* OR *Delocrania* OR *Dirphia* OR *Elymnia* OR *Euclea* OR *Euprosterina* OR *Hemisphaerota* OR *Hidari* OR *Hispoleptis* OR *Homaledra* OR *Homophylotis* OR *Leucothyreus* OR *Mahasena* OR *Mecistomela* OR *Megalopyge* OR *Mesocia* OR *Metisa* OR *Microtylopteryx* OR *Natada* OR *Oiketicus* OR *Omiodes* OR *Opisina* OR *Opsiphanes* OR *Parasa* OR *Phobetron* OR *Promecotheca* OR *Segestidea* OR *Setora* OR *Setothosea* OR *Sexava* OR *Stenoma* OR *Struthocelis* OR *Synale* OR *Talima* OR *Tropidacris* OR *Zophopetes*) AND ('chemical ecology' OR semiochemicals OR pheromone OR kairomone OR allomone OR synomone OR 'volatile compounds' OR VOC OR HIPV).

The search was carried out on September 12, 2023, using the descriptors, and 115 works were identified considering the characteristics of the research and the inclusion criteria (scientific articles) after initial filtering in the databases themselves. In the State of the Art through Systematic Review (StArt) tool (Zamboni et al., 2010), duplicate works were identified (n = 54) and analyzed per research topic. Works that did not present a description of compounds related to genera of Arecaceae-defoliating insects were excluded (n = 27). Thus, 34 studies were selected.

2.2. Arecaceae-defoliating pests

Insects considered defoliators feed on the leaf blade, causing partial or total plant defoliation. Furthermore, some insects can scrape the leaf's epidermal tissues or undermine the internal tissues between the upper and lower epidermis, causing drying and loss of leaves (Ferreira et al., 1998). These pests generally cause delays in plant development, reduce production, and cause premature fruit fall.

The main defoliators of Arecaceae are insects from the orders Lepidoptera, Coleoptera and Orthoptera (Table 1). The most diversity of species that attack palm trees is associated with the order Lepidoptera in different regions. They are critical pests, as in high infestations, they can cause complete plant defoliation and irreversible damage (Lemos & Boari, 2010). The second order is Coleoptera, mainly including insects from the Chrysomelidae family. Some Orthoptera species stand out as defoliators in Africa, Asia, and Oceania. Insects from the orders Phasmatodea (stick insects) and Hymenoptera (leaf-cutter ants) are also associated with cultivation regions but have little relevance (Howard et al., 2001). Lepidoptera are critical defoliators of palm trees across the planet and are characterized by their immature phase as phytophagous caterpillars. *Opisina arenosella* Walker, 1864 (Lepidoptera: Oecophoridae) and *Artona catoxantha* Hamps, 1892 (Lepidoptera: Zygaenidae) in Asia, *Agonoxena argaula* Meyrick, 1921 (Lepidoptera: Agonoxenidae) in Oceania, *Zophopetes cerymica* Hewitson, 1867 (Lepidoptera: Hesperidae) in tropical Africa, and *Brassolis sophorae* Linnaeus, 1758 (Lepidoptera: Nymphalidae) in the Americas are among the main species that stand out, in addition to several species of stinging caterpillars from the Limacodidae and Saturniidae families (Table 1).

The nutritional value and quantity of Arecaceae leaves consumed can directly influence the life cycle of defoliating insects, which may be longer or shorter depending on the host species. The oil palm leaf has a high content of indigestible cellulose fibres and a low nutritional value; therefore, a limited number of insects have evolved as defoliators of this palm tree (Howard et al., 2001). The larval stages of these insects generally develop slowly (Rodrigues et al., 2006). Furthermore, the abundance of caterpillars is lower in young leaves than in older leaves, possibly influenced by nutritional variation. It has also been observed that younger leaves may present a more significant number of secondary metabolites directly involved in plant defence against herbivory (Hartmann, 1996).

The abundance of *Opsiphanes invirae* Hübner, 1818 (Lepidoptera: Nymphalidae) caterpillars varies depending on the leaf region sampled, where the most significant number of caterpillars was observed on

leaflets 51–101, which corresponds to the intermediate part of the leaves (Oliveira et al., 2018a). The most significant number of *O. cassina* Felder (1862) caterpillars were observed on leaflets 41–80 due to the lower tannin and high nitrogen levels in this leaf region (González et al., 2011). Injuries caused by immature Nymphalidae species are characterized by feeding from the edges to the center of the leaves, regardless of the host and with partial or total consumption of the leaflets (Figure 1a). In oil palm, *O. cassina* can consume an average of 356.51 cm² of leaves in the field during its larval phase and is characterized by leaf feeding, leaving only the central vein of the leaflets (González et al., 2012). For the species *B. sophorae*, partial or total defoliation has been observed, with the caterpillars consuming 500–600 cm² of leaf area (between 2 and 2.5 leaflets). *Brassolis isthmia* Bates, 1864 (Lepidoptera: Nymphalidae) presented an average consumption of 820.62 cm² during the larval phase (Lemos & Boari, 2010; Mexzón, 2011). In the Limacodidae family, a high consumption rate for the caterpillar *Acharia fusca* Stoll, 1999 (Lepidoptera: Limacodidae), which consumes around 402.31 cm² of *Elaeis guineensis* leaf area (Martínez et al., 2014), has been observed in the laboratory. In high infestations, these species can cause complete plant defoliation in a few days (Figure 1b), demonstrating the importance of monitoring for decision making in managing these pests.

In the order Coleoptera, attack by defoliating insects is not restricted to the immature phase; in some species, the adults feed on leaves, such as *Leucothyreus femoratus* Burmeister, 1844 (Coleoptera: Scarabaeidae), a significant pest in the regions of Central America, Colombia and Venezuela, where they are rhizophagous in the larval stage and feed from the edge of the leaflets as adults, consuming an average of 13 mm² per day (Martínez et al., 2000; Martínez et al., 2013). In South America, *Coraliomela* spp. exhibits this behavior, with the adults feeding on the parenchyma, drawing a straight line parallel to the central vein of the coconut leaflets. However, the most significant damage is caused by the larva, which feeds by making holes in the leaves, reducing the leaf area of the young palm plant and causing delays in plant development (Ferreira et al., 1998; Manca et al., 2014).

In the Orthoptera order, species from the Tettigoniidae family are considered the main defoliating pests of oil palm crops in Papua New Guinea (Oceania), with species of the genus *Sexava* reported as the most critical, where the combined attack of overlapping generation cycles is more harmful and causes a reduction in the photosynthetic surface area of the leaflets and, consequently, a decrease in fruit production in the affected palm trees (Ero et al., 2013). With generalist habits, the species *Aularches miliaris*

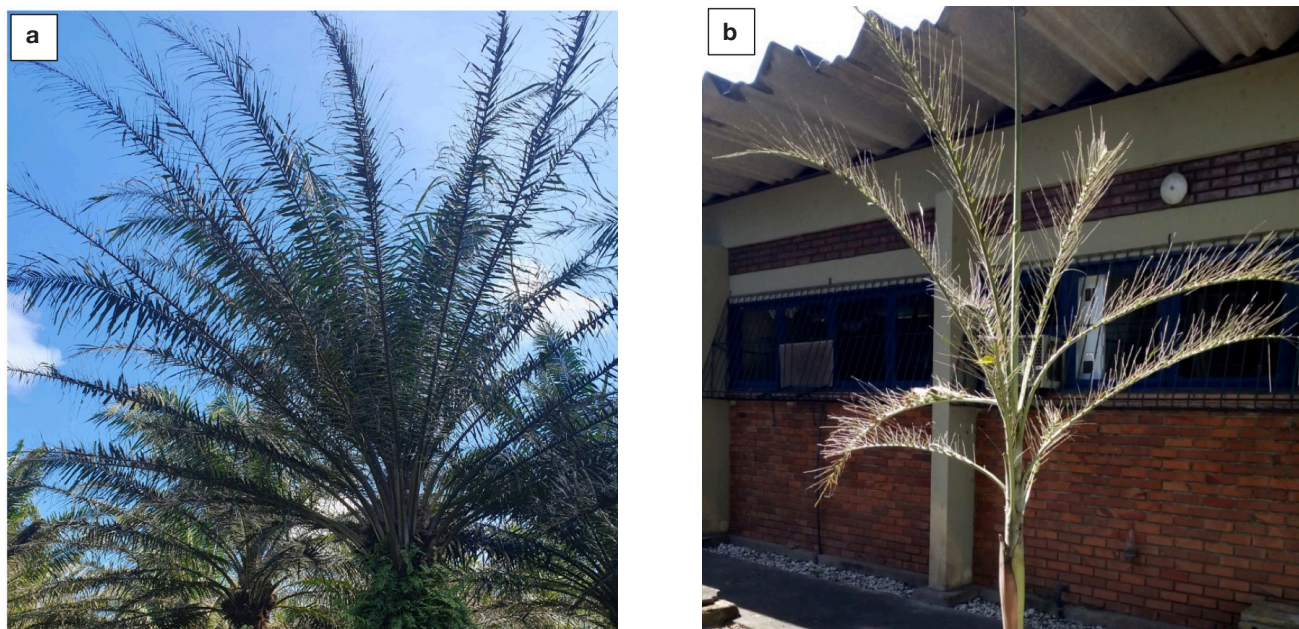
Table 1. Main defoliating insect pests of Arecaceae and their geographic distribution — *Principaux insectes nuisibles défoliateurs des Arecaceae et leur répartition géographique.*

Order	Family	Species*	Distribution**
Coleoptera	Chrysomelidae	<i>Alurnus humeralis</i>	Colombia and Ecuador
		<i>Brontispa longissima</i>	Africa, Asia and Oceania
		<i>Cephaloleia vagelineata</i>	Colombia and Ecuador
		<i>Coelaenomenodera minuta</i>	Africa
		<i>Coraliomela brunnea</i>	South America
		<i>Delocrania cossyphoides</i>	South America
		<i>Hemisphaerota cyanea</i>	United States
		<i>Hispoleptis subfasciata</i>	Colombia
		<i>Mecistomela marginata</i>	Brazil
		<i>Promecotheca</i> spp.	Asia and Oceania
	Scarabaeidae	<i>Adoretus sinicus</i>	Asia, North America and Oceania
		<i>Leucothyreus femoratus</i>	Central America, Colombia and Venezuela
	Lepidoptera	Coleophoridae	<i>Homaledra</i> sp.
Crambidae		<i>Omiodes blackburni</i>	Hawaii and Papua New Guinea
Elachistidae		<i>Agonoxena argaula</i>	
		<i>Antaeotricha</i> sp.	Oceania and Hawaii
		<i>Americas</i>	
Hesperiidae		<i>Stenoma cecropia</i>	Central America and Colombia
		<i>Hidari irava</i>	Southeast Asia
		<i>Synale hylaspes</i>	South America
Limacodidae		<i>Zophopetes cerymica</i>	Africa
		<i>Acharia</i> spp.	Américas
		<i>Contheyla rotunda</i>	India
		<i>Darna</i> spp.	Asia
		<i>Euclea</i> spp.	Central and South America
		<i>Euprosterina elaeasa</i>	Central and South America
		<i>Natada subcpectinata</i>	Central and South America
		<i>Parasa</i> spp.	Asia
		<i>Phobetron hipparchia</i>	Central and South America
		<i>Setora nitens</i>	Asia and Colombia
		<i>Setothosea asigna</i>	Asia and Colombia
		<i>Talima</i> spp.	Central and South America
		Megalopygidae	<i>Mesocia pusilla</i>
<i>Megalopyge albicollis</i>			Central and South America
Nymphalidae		<i>Amathusia phidippus</i>	Asia
	<i>Brassolis sophorae</i>	Central and South America and Thailand	
	<i>Elymnias hypermnestra</i>	Asia	
	<i>Opsiphanes invirae</i>	Central and South America	
	<i>Opsiphanes cassina</i>	Central and South America	
	<i>Struthocelis semiotarsa</i>	Colômbia	

Table 1 (continued). Main defoliating insect pests of Arecaceae and their geographic distribution — *Principaux insectes nuisibles défoliateurs des Arecaceae et leur répartition géographique.*

Order	Family	Species*	Distribution**
Lepidoptera	Psychidae	<i>Mahasena corbetti</i>	Asia and Oceania
		<i>Metisa plana</i>	Asia
		<i>Oiketicus kirbyi</i>	Central and South America
	Saturniidae	<i>Automeris liberia</i>	South America
		<i>Dirphia gragatus</i>	Central and South America
	Xyloryctidae	<i>Opisina arenosella</i>	Asia
Zygaenidae	<i>Artona catoxantha</i>	Asia and Suriname	
	<i>Homophylotis catori</i>	Africa	
Orthoptera	Acrididae	<i>Microtylopteryx hebaridi</i>	Central America
	Pyrgomorphidae	<i>Aularches miliaris</i>	Asia and Oceania
	Romaleidae	<i>Tropidacris cristata</i>	Central and South America
	Tettigoniidae	<i>Segestidea</i> spp.	Africa and Papua New Guinea
		<i>Sexava</i> spp.	Africa and Papua New Guinea

Sources: *: Ferreira et al., 1998; Howard et al., 2001; Martínez et al., 2009; Oliveira et al., 2018; **: CABI, 2023; GBIF Secretariat, 2023.

**Figure 1.** Defoliation caused by the attack of Nymphalidae species caterpillar on Arecaceae in Brazil — *Défoliation causée par l'attaque de la chenille d'espèces de Nymphalidae sur les Arecaceae au Brésil.*

a. Cultivation of *Euterpe oleracea* in Tailândia, Pará, Brazil — *Culture d'Euterpe oleracea à Tailândia, Pará, Brésil.* **b.** Total defoliation of *Veitchia merrillii* ornamental in Rio Largo, Alagoas, Brazil — *Défoliation totale de Veitchia merrillii ornementale à Rio Largo, Alagoas, Brésil.*

Linnaeus, 1758 (Orthoptera: Pyrgomorphidae) is associated with attacks in coconut and oil palm areas in Southeast and South Asia (Mathew et al., 2021).

In some regions, important Arecaceae-defoliating species are still poorly studied with respect to their

behavior and the development of techniques that can contribute to integrated management of these pests. In Colombia, a campaign is being developed to monitor, prevent and intervene in the integrated management of defoliating pests in oil palm crops that

implements an action plan based on the diagnosis for species that predominate in the region (Martínez et al., 2009). However, there is a lack of action related to technological advances for implementing management programs for these pests, making cultivation unfeasible. As occurs in the development and use of pheromones, despite advances, the accessibility of these products to potential users is compromised by a deficiency in technology transfer to producers (Moreira et al., 2005; Goulart et al., 2015).

2.3. Pheromones of Arecaceae-defoliating pests

Using pheromones to control Arecaceae insect pests is an established practice for monitoring and control and contributes to integrated pest management in several producing regions. Among the insects considered defoliators in the order Lepidoptera, studies on eight genera have been published, including the description of the organic chemical compounds used as sex pheromones, most of which were extracted from glands present in females (**Table 2**).

Pheromones are chemicals produced by specialized glands that affect insect behavior, development and physiology. They are classified according to their effects; they can have a preparatory effect (more extended action) or a triggering effect (immediate action) (Nordlund & Lewis, 1976; Ferreira & Zarbin, 1998). The presence of abdominal scent glands is a common characteristic of lepidopterans, mainly female moths. In this respect, moths differ from butterfly species, which have release structures in androconia on the wings, tufts of scales, or specialized bristles at the end of the abdomen of males. These structures can release compounds with short- and long-range action as pheromones, and the structure is often similar to plant secondary metabolites or fatty acid derivatives (Ganai et al., 2017).

Some species observed in the survey were not associated with Arecaceae pests (**Table 2**). However, this evidence can help to guide studies on chemical ecology with species of the same genus, about sexual behavior, odorous compound release structures, types of compounds and forms of use in the field. The

Table 2. Compounds described as pheromones for genera of the order Lepidoptera associated with defoliating species of Arecaceae — *Composés décrits comme des phéromones pour les genres de l'ordre Lepidoptera associés aux espèces défoliantes d'Areceae*.

Family	Genus	Species	Origin	Compounds	References
Limacodidae	<i>Darna</i>	<i>D. trima</i>	Female abdominal glands	Methyl (<i>E</i>)-7,9-decadienoate	Sasaerila et al., 2000a Siderhurst et al., 2007
		<i>D. bradleyi</i>		Isobutyl (<i>E</i>)-7,9-decadienoate	
		<i>D. pallivitta</i>		2-Methylbutyl (<i>E</i>)-7,9-decadienoate (<i>E</i>)-2-Hexenyl(<i>E</i>)-7,9-decadienoate n-Butyl (<i>E</i>)-7,9-decadienoate	
	<i>Parasa</i>	<i>P. lepida</i>	Female abdominal glands	(<i>Z</i>)-7,9-Decadien-1-ol	
	<i>Setora</i>	<i>S. nitens</i>	Female glands	(<i>Z</i>)-9-Dodecenal (<i>Z</i>)-9,11-Dodecadienal	Sasaerila et al., 2000b
	<i>Setothosea</i>	<i>S. asigna</i>	Female glands	(<i>E</i>)-9-Dodecenal (<i>E</i>)-9,11-Dodecadienal	Sasaerila et al., 1997
Nymphalidae	<i>Elymnias</i>	<i>E. thryallis</i>	Female glands	(<i>S</i>)-2-Methyl-1-(4-methyl-2-furyl)-3-buten-2-ol (<i>E</i>)-4-Methyl-(2-methyl-1,3-butadienyl) furan (<i>Z</i>)-4-Methyl-(2-methyl-1,3-butadienyl) furan 3,9-Dimethyl-1,6-dioxaspiro[4,5] dec-3-ene	Schulz et al., 1996
Oecophoridae	<i>Opisina</i>	<i>O. arenosella</i>	Female glands	(<i>Z,Z,Z</i>)-3,6,9-Tricosatriene	Bhanu et al., 2018
	<i>Stenoma</i>	<i>S. catenifer</i> <i>S. cecropia</i>	Female glands	(<i>Z,E</i>)-9,11,13-Tetradecatrienal (<i>Z,E</i>)-9,11-Tetradecadienal (9 <i>Z</i>)-9,13-Tetradecadien-11-inal	Millar et al., 2008 Zagatti et al., 1996
Psychidae	<i>Oiketicus</i>	<i>O. kirbyi</i>	Expelled substance by the female	(<i>R</i>)-1-Methyl butyl octanoate (<i>R</i>)-1-Methyl butyl nonanoate (<i>R</i>)-1-Methyl butyl decanoate (<i>R</i>)-1-Methyl pentyl decanoate (<i>R</i>)-1-Methyl butyl dodecanoate	Rhainds et al., 1994

following stinging caterpillars were among the species considered defoliating pests of Arecaceae observed in the surveys: *Darna trima* Moore, 1859; *D. bradleyi* Holloway, 1986; *D. pallivitta* Moore, 1877; *Setothosea asigna* van Eecke, 1929; *Setora nitens* Walker, 1855 and *Parasa lepida* Cramer, 1779 (Lepidoptera: Limacodidae). Field studies have used synthetic sex pheromones identified from female glands (Sasaerila et al., 1997, 2000a, 2000b; Siderhurst et al., 2007) in the capture of males using delta-type traps to monitor or control these pests in commercial oil palm plantations in Southeast Asia (Sasaerila et al., 2007).

For species of the genus *Darna*, the decadienoates 2-methylbutyl (*E*)-7,9-decadienoate and (*E*)-2-hexenyl (*E*)-7,9-decadienoate in combination have been shown to be essential and synergistic components of pheromones for attracting *D. trima* males. For *D. bradleyi*, the compound isobutyl (*E*)-7,9-decadienoate individually attracts males but the addition of methyl (*E*)-7,9-decadienoate in a ratio of 1:10 significantly increased the attractiveness of the female bait (Sasaerila et al., 2000a).

In field tests with *D. pallivitta*, males were attracted to bait containing n-butyl (*E*)-7,9-decadienoate, which outperformed attractive baits with virgin moths (Siderhurst et al., 2007; Jang et al., 2009). The use of the pheromone showed the potential to control *D. pallivitta* through the interruption of mating using traps and by the interruption of communication through a species carrying the pheromone (*Bactrocera cucurbitae* [Coquillett, 1899] [Diptera: Tephritidae]) to disrupt the everyday mating communications of the target pest (Siderhurst et al., 2015).

In the search for the sex pheromone of *S. assigna*, seven active compounds were identified through gas chromatography and electroantennography analysis. However, only two have demonstrated efficiency in field capture experiments, the aldehydes (*E*)-9-dodecenal and (*E*)-9,11-dodecadienal in a 1:1 ratio but not alone (Sasaerila et al., 1997). In studies with *S. nitens* using mass spectrometry and electroantennography analyses, the components of the pheromone of this species were the isomers corresponding to the aldehydes identified as components of the *S. assigna* pheromone (*Z*)-9-dodecenal and (*Z*)-9,11-dodecadienal, and they were efficient in a 1:1 ratio, as verified through a field experiment carried out with synthetic compounds in Malaysia (Sasaerila et al., 2000b).

These sympatric and co-seasonal species in oil palm plantations remain reproductively isolated through specificity in their intra- and interspecific communication signal, which affects their daily periodicity and micro-location for chemical signalling (Sasaerila et al., 2000c). However, the application of these described sex pheromones in managing stinging caterpillars is poorly documented. The stinging

caterpillar, *P. lepida*, a defoliating pest of coconut trees in southwest Asia, has also been found on coffee, mango and cocoa plantations (Sawada et al., 2008). The sex pheromone of this pest was extracted from the glands of virgin females, and the identified compound (*Z*)-7,9-decadien-1-ol (*Z*7,9-10:OH) showed efficiency in capturing males in the field with sticky traps using rubber septa as a release during 12 days of exposure (Wakamura et al., 2007; Islam et al., 2009).

In coconut cultivation in India, the sex pheromone (*Z,Z,Z*)-3,6,9-tricosatriene can be used to capture the masses of *Opisina arenosella* Walker, 1864 (Lepidoptera: Oecophoridae), a critical defoliating species. The use of white 'pinwheel' traps placed in the middle of the palm tree canopy make it an efficient technique to control this pest (Muniyappa et al., 2018). This sex pheromone was identified in extracts from the glands of one-day-old females (Bhanu et al., 2018). Females of *O. arenosella* are attracted to kairomones (linalool, acetophenone and limonene) found in coconut leaves and larval excreta; in oviposition preference tests, these volatiles have been used to enhance the semiochemical-based management method for this pest (Kumara et al., 2015; Shameer et al., 2017).

The aldehyde compounds (*Z,E*)-9,11,13-tetradecatrienal and (*Z,E*)-9,11-tetradecadienal are considered components of the sex pheromone of *Stenoma cecropia* Meyrick, 1916 (Lepidoptera: Elachistidae) and have been identified in extracts from female glands and tested using electroantennography, laboratory olfactometry and trap experiments in an oil palm cultivation area in Colombia. Attraction to males was observed only with the use of a blend consisting of the two aldehydes identified in proportions of 83% for (*Z,E*)-9,11,13:Ald and (*Z,E*)-9,11,14:Ald and 17% for (*Z,E*)-9,11-14:Ald, but lower capture rates were observed compared to those obtained using virgin females as bait (Zagatti et al., 1996).

An important pest of avocado fruit, *Stenoma catenifer* Walsingham, 1912 also produces an unsaturated aldehyde compound, (*Z*)-9,13-tetradecadien-11-inal, as a pheromone, and it attracted more males in field tests compared to caged virgin female moths, demonstrating the frequent relationship that occurs with congeneric species in the identification of compounds used as pheromones (Millar et al., 2008; Hoddle et al., 2009). In commercial avocado orchards, parameters for using the pheromone were observed, such as the type of bait, height, trap density and bait effectiveness time, in which grey or white rubber septa are the best releasers in avocado traps. Type Pherocon IC wings (Trécé Inc., Adair, OK, USA), at a height between 4 and 6 m with a distribution of three traps per hectare, captured the most males per trap in 15 days (Hoddle et al., 2011; Cruz-López et al., 2020; Velázquez-Martínez et al., 2023). Males

were captured using the sex pheromone of *S. catenifer* throughout the year, with population peaks in June–August and December–January, with the additional influence of food abundance, climate (precipitation and temperature) and altitude. Furthermore, this pheromone attracted the species *Antaeotricha nictitans* Zeller, 1854 (Lepidoptera: Elachistidae) of unknown hosts (Castillo et al., 2012; Vázquez et al., 2017; Velázquez-Martínez et al., 2022), and this genus is considered a defoliating pest of Arecaceae (**Table 1**).

The basket bug, *Oiketicus kirbyi* Guiding, 1827 (Lepidoptera: Psychidae), a pest associated with several commercial crops, is also reported to defoliate palm trees (Oliveira et al., 2018b). Females release the sex pheromone to attract males to the lower portion of the baskets. This pheromone has been identified as a mixture of five chiral esters, (*R*)-1-methylbutyl octanoate, (*R*)-1-methylbutyl nonanoate, (*R*)-1-methylpentyl decanoate, (*R*)-1-methylbutyl and (*R*)-1-methylbutyl decanoate, the latter being the majority compound. In field tests in oil palm plantations, the mixture with 1,000 µg of the main compound and 100 µg of the other compounds in different combinations attracted males, demonstrating their potential utility in the management of *O. kirbyi* populations (Rhains et al., 1994).

Evidence of sex pheromones has also been reported for *Metisaplano* Walker, 1883 (Lepidoptera: Psychidae), a critical defoliator in oil palm plantations in Malaysia (Abdullah et al., 2012). The use of receptive females in sticky traps resulted in the mass capture of moths in the field, reducing leaf damage by 35–45% in the capture blocks tested. The use of traps with females and aerial spraying of *Bacillus thuringiensis* (Bt) reduced the caterpillar population by 94% in the first cycle of the caterpillar population (Kamarudin et al., 2010; Ahmad et al., 2017). Furthermore, false pheromone trails generated by the increase in the number of females of the same species per palm tree can interrupt the natural mating of this pest in oil palm crops (Rhains, 2018).

Regarding the genus *Elymnia*, species with pheromones described in the literature are not pests associated with Arecaceae (*Elymnia thryallis* Kirsch, 1876 [Lepidoptera: Satyridae]), which produces elymniafuran ((*S*)-2-methyl-1-(4-methyl-2-furyl)-3-buten-2-ol), formulated as small amounts of (*E*)- and (*Z*)-4-methyl-(2-methyl-1,3-butadienyl) furan and 3,9-dimethyl-1,6-dioxaspiro [4,5] dec-3-ene (Schulz et al., 1996). Observations from these studies can contribute to research on the species *E. hypermnestra*, which is a critical defoliator found in oil palm plantations in South Asia (**Table 1**).

Lepidoptera pheromones are varied and classified according to their general chemical structure during biosynthesis (Ando & Yamamoto, 2020). Around 75% of these compounds are classified as type I pheromones, which are biosynthesized *de novo* via general saturated

fatty acids comprising the classes alcohols, aldehydes and acetates, mono- or diunsaturated and containing 10–18 carbon atoms in their chain. Type II pheromones represent approximately 15% of known lepidopteran pheromones and have been identified only from some limited groups of compounds, such as polyunsaturated hydrocarbons and their epoxides (Allison & Cardé, 2016; Ando & Yamamoto, 2020; Jurenka, 2021).

In addition to these, there are also type III pheromones, branched hydrocarbons, type 0 pheromones, secondary alcohols and short-chain ketones (7–9 carbon atoms), which are considered a more ancestral type of Lepidoptera pheromone. Other types include terpenes and their derivatives, methyl ketones, secondary alcohols with methyl groups as branches and unsaturated ketones (Allison & Cardé, 2016).

The presence of saturated and unsaturated esters has been observed in the chemical classification of pheromones from insect pests of genera of the order Lepidoptera that are associated with Arecaceae defoliators (**Figure 2a**). These compounds as well as alcohols and aldehydes (**Figure 2b**) are considered type I pheromones and are quite common in Lepidoptera species (Jurenka, 2021). This type of pheromone, generally derived from fatty acids, originates from palmitic and stearic acids, which, in turn, are produced in the pheromone gland in the female abdomen (Allison & Cardé, 2016). Type I compounds with the presence of saturated and unsaturated esters have been identified as pheromone components for species of the genera *Darna* and *Oiketicus* (**Figure 2a**), and alcohols and aldehydes have been identified in the genera *Setora*, *Setothosea*, *Stenoma* and *Parasa* (**Figure 2b**). Other pheromones found and described for these Lepidoptera species include terpenoids and polyunsaturated hydrocarbons (**Figure 3**).

The compound (*Z,Z,Z*)-3,6,9-tricosatriene, described as a pheromone component from species of the genus *Opisina*, is considered a type II pheromone. This type of pheromone is derived from linoleic or linolenic acids obtained from the insect's diet, maintaining the pattern of two or three *Z* double bonds separated by a methylene group (CH₂) (Ando & Yamamoto, 2020; Jurenka, 2021). Pheromones of the genus *Elymnia* include terpenoids (**Figure 3**). Among lepidopteran species of Arecaceae pests, eight species of the Limacodidae family that produce pheromones have been reported in the literature, with studies concentrated in Southeast Asia, Central and South America, and Africa. The pheromones belong to the classes of unsaturated alcohols, esters and aldehydes with chains containing 8–20 carbons. Polyunsaturated alkenes have also been reported, and all identified compounds share the same biosynthetic pathway (Reis et al., 2023).

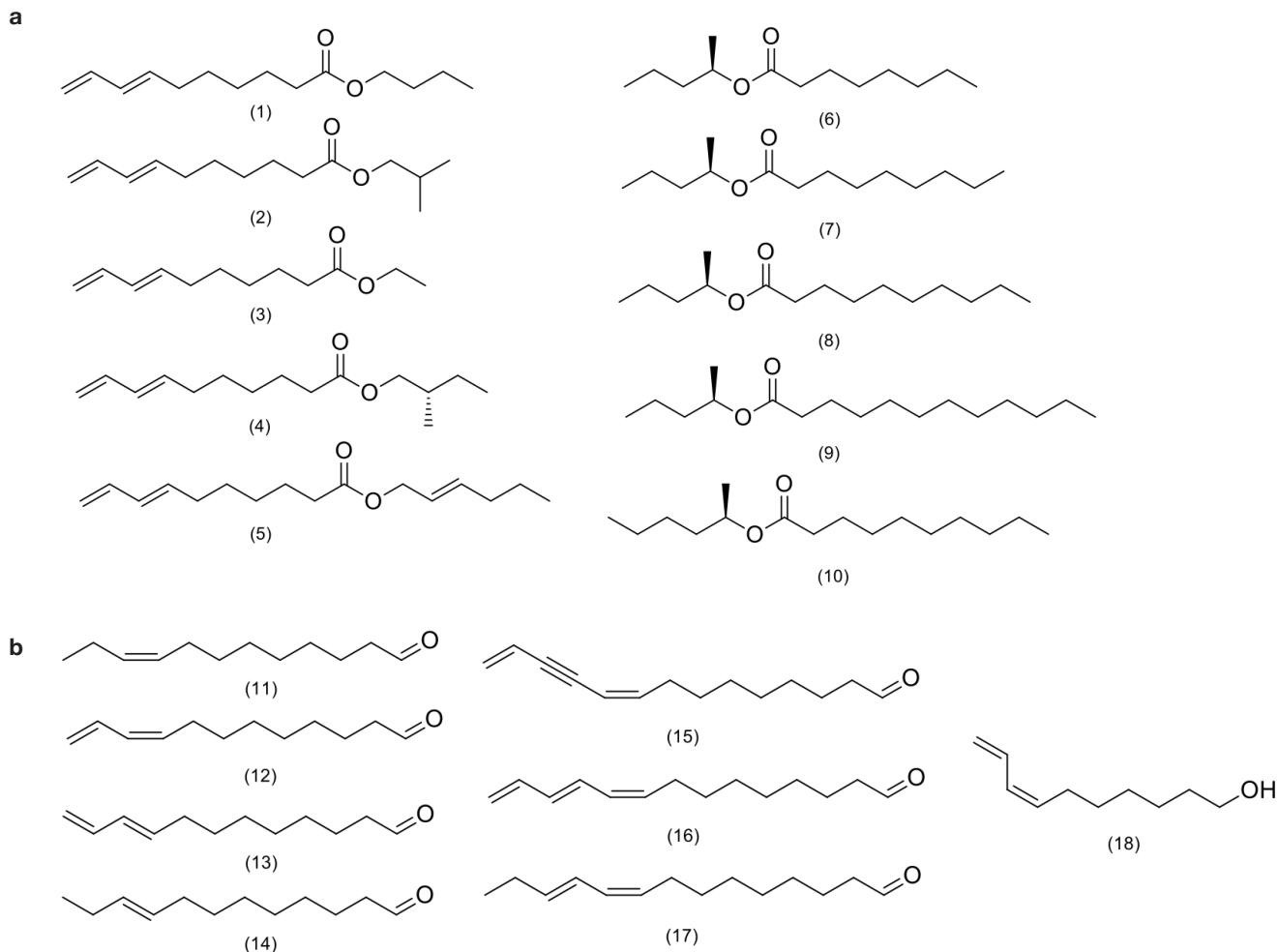
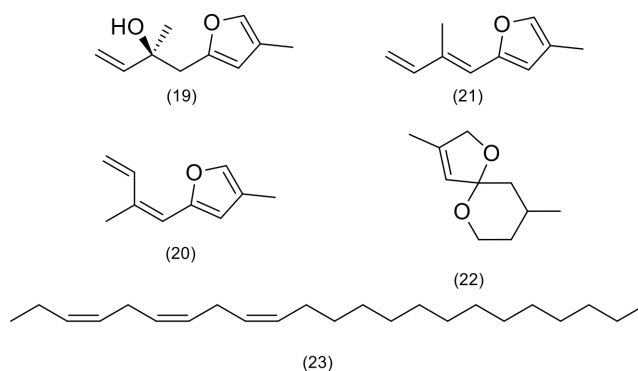


Figure 2. Type I pheromones of Lepidoptera order insect pests associated as defoliators of Arecaceae — *Les phéromones de type I de l'ordre des insectes ravageurs Lepidoptera, associées aux défoliateurs d'Arecaceae.*

a. Saturated and unsaturated esters — *Esters saturés et insaturés*; **b.** Alcohols and aldehydes — *Alcools et aldéhydes*; (1) butyl (E)-7,9-deca-dienoate; (2) isobutyl (E)-7,9-decadienoate; (3) ethyl (E)-7,9-decadienoate; (4) (S,E)-2-methylbutyl 7,9-decadienoate; (5) (E)(E)-2-hexenyl 7,9-decadienoate; (6) methylbutyl octanoate; (7) methylbutyl nonanoate; (8) methylbutyl decanoate; (9) methylbutyl dodecanoate; (10) methylpentyl decanoate; (11) (Z)-9-dodecenal; (12) (Z)-9,11-dodecadienal; (13) (E)-9,11-dodecadienal; (14) (E)-9-dodecenal; (15) (Z)-9,13-tetradecadien-11-ynal; (16) (Z,E)-9,11,13-tetradecatrienal; (17) (Z,E)-9,11-tetradecadienal; (18) (Z)-7,9-decadien-1-ol.

Figure 3. Terpenoid class pheromones and polyunsaturated hydrocarbon of Lepidoptera order insect pests associated as defoliators of Arecaceae — *Phéromones de classe terpénoïde et hydrocarbures polyinsaturés de l'ordre des insectes ravageurs lépidoptères, associées aux défoliateurs d'Arecaceae.*

(19) (S)-2-methyl-1-(4-methylfuran-2-yl)but-3-en-2-ol; (20) (Z)-4-methyl-2-(2-methylbuta-1,3-dien-1-yl)furan; (21) (E)-4-methyl-2-(2-methylbuta-1,3-dien-1-yl)furan; (22) 3,9-dimethyl-1,6-dioxaspiro[4.5]dec-3-ene; (23) (Z, Z, Z)-3,6,9-tricosatriene.



For the order Coleoptera, there are descriptions of active compounds identified for the genus *Brontispa* Sharp, 1904 (Coleoptera: Chrysomelidae), characterized as allelochemicals emitted by the coconut tree. The mixture of leaf compounds β -myrcene, (-)-limonene and *E*-2-hexen-1-ol, demonstrated attractiveness for males and females and the induction of oviposition, which is important in modulating insect behavior (Fang et al., 2011). Evidence regarding the use of pheromones by *B. longissima* (Gestro, 1885) is associated with the presence of proteins involved in the reception and detection of odorants in antennal transcriptomes (Bin et al., 2017). Furthermore, the contact sex pheromone of this pest consists of one or more polar compounds, which are likely saturated hydrocarbons present in the elytra of females (Kawazu et al., 2011).

Indications for chemical recognition in the form of sex pheromones have also been observed among adults of *Leucothyreus marginaticollis* Blanchard, 1843 (Coleoptera: Scarabaeidae) during mating behavior (Ferreira & Rodrigues, 2017).

Studies on chemical ecology have not been performed with genera of the order Orthoptera that are *Arecaceae* defoliators (**Table 1**). However, as some species of grasshopper present gregarious, migratory behavior, are generalist defoliators and considered insect pests of great importance worldwide, most chemoreception and chemical ecology studies for this order have focused on species with these characteristics, such as *Locusta migratoria* (Linnaeus, 1758) and species of *Schistocerca* spp. (Orthoptera: Acrididae). These pests preferentially occupy open areas and cause

clouds of locusts that migrate and attack large areas of plantations, including coconut and oil palm crops in regions of Asia, Africa and some parts of South America (Howard et al., 2001).

Aggregation pheromones, such as common compounds found in body parts and faecal droppings that are emitted by species of *Schistocerca* spp. and *L. migratoria*, anisole, veratrole, benzaldehyde, 4-vinylanisole, guaiacol, phenol and phenyl acetonitrile, are an essential tool for managing *Orthoptera* species (**Figure 4**) (Torto et al., 1994; Mahamat et al., 2000; Wei et al., 2017). Volatiles originating from excrement are guaiacol and phenol and are components of the aggregation pheromone of *S. gregariae* Forskål, 1775 (Torto et al., 1996; Dillon et al., 2002).

Phenylacetonitrile (PAN), which is emitted by sexually mature males, is involved in sexual behavior as a repellent during mating and inhibits competition from other males (Seidelmann & Ferenz, 2022). PAN, as an aposematic compound, is also a component of the locust defense mechanism, signaling toxicity to predators (Wei et al., 2019). This compound, together with (*Z*)-2-octen-1-ol and (*Z*)-3-nonen-1-ol, is released explicitly by males in an agglomeration of *S. piceifrons* Walker, 1870, and although they do not show any attractive or repellent effect, these compounds are related to female mating partner evaluation pheromones (Stahr et al., 2016).

(*Z*)-3-nonen-1-ol produced by gregarious males of *S. americana* Drury, 1773 is involved in sexual behavior as an anti-aphrodisiac and has the effect of accelerating maturation, enabling the synchronization of sexual development (Stahr et al., 2013). In

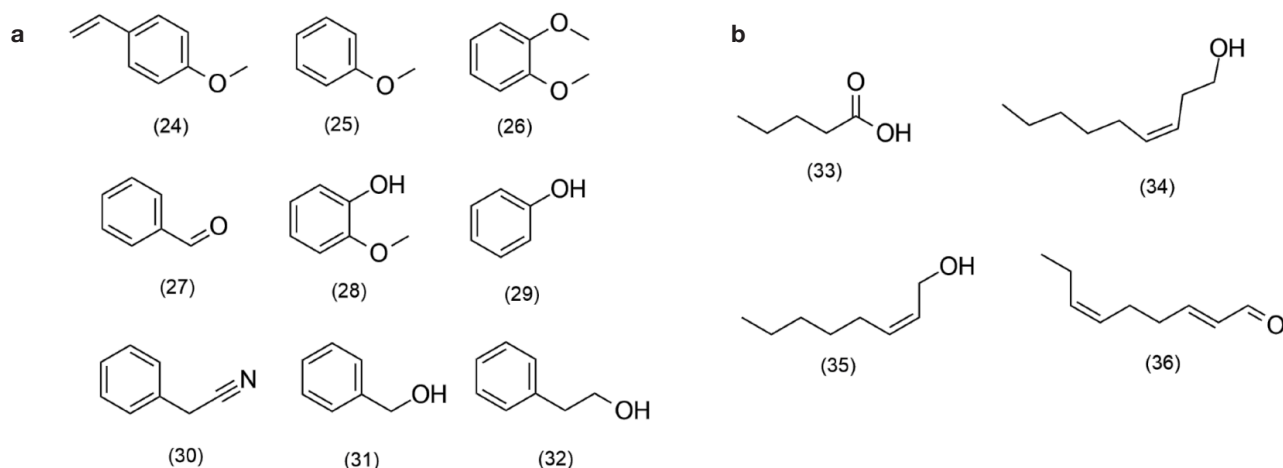


Figure 4. Pheromones described for species of *Schistocerca* spp. and *Locusta migratoria*: 4-vinylanisole (24), anisole (25), veratrol (26), benzaldehyde (27), guaiacol (28), phenol (29), phenylacetonitrile (30), benzyl alcohol (31), 2-phenylethanol (32), pentanoic acid (33), (*Z*)-3-nonen-1-ol (34), (*Z*)-2-octen-1-ol (35), (*E,Z*)-2,6-nonadienal (36) — *Phéromones décrites pour les espèces de Schistocerca spp. et Locusta migratoria* : 4-vinylanisole (24), anisole (25), veratrol (26), benzaldéhyde (27), guaiacol (28), phénol (29), phénylacetonitrile (30), alcool benzylique (31), 2-phényléthanol (32), acide pentanoïque (33), (*Z*)-3-en-nonol-1-ol (34), (*Z*)-2-octen-1-ol (35), (*E,Z*)-2,6-nonadienal (36).

S. cancellata Serville, 1838, volatile male-specific benzyl alcohol and 2-phenylethanol are emitted almost exclusively from the abdomen, with an intensity influenced by sexual competition between males (Seidelmann & Stahr, 2023). Released by the glands of adult *S. gregaria* females, pentanoic acid has been shown to stimulate pre-mating behavior in males (Njagi & Torto, 2002).

The only pheromone for the solitary grasshopper is (*E,Z*)-2,6-nonadienal, which is released by solitary *S. gregaria* females and known to induce behavioral attraction to males (Ochieng & Hansson, 1999).

The volatile compounds emitted in the fecal excrement of *L. migratoria* are the same as those described for species of the genus *Schistocerca*. However, only 4-vinylanisole has the action of attracting solitary and gregarious grasshoppers, regardless of age or sex, and experimental populations and wild animals in the field (Wei et al., 2017; Guo et al., 2020). These compounds, although common between species, present differences in emission dynamics, given that relative concentrations in pheromone mixtures provide specific signals for each species, sex and developmental stage (Nakano et al., 2022).

In the intra- and interspecific aggregation of these species, a smaller pattern of stage and sex differentiation has been observed for the aggregation pheromone of *L. migratoria*, in which adults respond to the nymphs' pheromone, and the pheromone is emitted by both males and females. In contrast, there is no aggregative response between stages in *S. gregaria*, and pheromone production is specific to males (Niassy et al., 1999).

The compounds observed for *Orthoptera* species are simple aromatics (Figure 4) and used as pheromones in communication and as defense compounds (Brückner et al., 2020). Within the order *Orthoptera*, fatty acid derivatives, such as alcohols and aldehydes, which are common compounds for insect pest species of the order *Lepidoptera*, have also been observed (Figure 4).

The use of these compounds in traps for monitoring and controlling species in the field has rarely been discussed in the literature, being restricted to experiments to verify attraction under reduced sampling conditions. Research that contributes to the development of management strategies using the pheromones described is needed to enable progress in the prevention and control of locust outbreaks.

Many of the pheromones studied require field validation, and a very small number are available on the market, such as the *O. arenosella* pheromone used for monitoring and control in India. This highlights the need for chemical synthesis of identified pheromones and further field studies to improve formulations, release strategies and trap types, which are fundamental variables for pheromone application as a tool for pest

monitoring and control. In addition, for substances already in use, continuous studies are necessary to maintain the efficiency of these products in the field.

Around 80% of insect species that are considered Arecaceae pests have not yet been studied for the identification of pheromones. This may be related to the expansion of monocultures, where insects that are not important can become pest insects, thus demonstrating an open field of research for the development of studies aiming at monitoring and control.

3. CONCLUSIONS

The studies evaluated in this survey focused on defoliating insects from crops distributed in Southeast and South Asia, which have the highest production of oil palm and coconut in the world. However, other tropical regions that produce Arecaceae crops, such as Central and South America, also have critical species of defoliating caterpillars, such as those from the family *Nymphalidae* (*B. sophorae* and *O. invirae* Hübner, 1818) and *Saturniidae* (*Automeris liberia* Cramer, 1780) (Calvache et al., 2010). These species are the subject of studies for developing pheromones to contribute to integrated pest management. Evidence of pheromone use was observed for *A. liberia* with the characterization of sensilla involved in recognizing pheromone molecules in males and females (Silva et al., 2019).

These contributions to the literature are necessary given the diversity of insect pests and forms of cultivation, even for insects that are not considered main pests, considering that climate change can affect the growth and distribution of pest species, the expansion of their geographic distribution, and the increase in their survival and number of generations. Thus, strategies should focus on intensive monitoring of these insect populations, as the leading management practice for dealing with changes in pest status (Skendžić et al., 2021; Yasin & Rehman, 2021).

Semiochemicals are essential tools for monitoring these pests; however, to ensure practical use in the field, it is necessary to improve existing techniques, with a particular emphasis on environmental factors, such as relative humidity, temperature and air speed, which can have an impact on how pheromones are used under these conditions (Andrew & Hill, 2017). Additionally, active substances should be studied in insects for which they have not yet been identified.

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