Journal of Sustainability Science and Management
Volume 19 Number 11, November 2024: 39-54
eISSN: 2672-7226

TOTAL PHENOLIC AND FLAVONOID CONTENT IN THE ESSENTIAL OILS OF SELECTED PLANTS AND ITS INSECTICIDE ACTIVITY FOR SUSTAINABLE CONTROL OF RED PALM WEEVIL (*Rhynchophorus ferrugineus*)

TAY KARH YAN[1], WAHIZATUL AFZAN AZMI[1], FAIZATUL SHIMAL MEHAMOD[1], NOR OMAIMA HARUN[1,2], AZILA ADNAN[1,2] AND HAZLINA AHAMAD ZAKERI[1,2]*

[1]*Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia.*
[2]*EnviroGroup, Biological Security and Sustainability Research Interest Group, Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia.*

**Corresponding author: hazlina@umt.edu.my*
http://doi.org/10.46754/jssm.2024.11.003
Received: 20 February 2024 *Accepted: 29 July 2024* *Published: 15 November 2024*

Abstract: Essential oils offer a promising alternative to chemical pesticides, which pose environmental and health risks. However, comprehensive field studies evaluating their long-term effectiveness and practical application in diverse agricultural settings are lacking. This study investigates the insecticidal efficacy of essential oils from four plants: *Cymbopogon citratus* (lemongrass), *Melaleuca cajuputi* (gelam), *Vitex rotundifolia* (beach vitex), and *Pandanus amaryllifolius* (pandan) to control the red palm weevil (*Rhynchophorus ferrugineus*, RPW). The oils were assessed for their antifeedant and repellent properties to contribute to sustainable pest management strategies. *Gelam* oil had the highest levels of phenolics and flavonoids, while *pandan* oil had the lowest. Prickmark analysis revealed that lemongrass oil had the greatest deterrent effect against RPW feeding, followed by *gelam* and beach vitex, with *pandan* oil showing no antifeedant activity. A Y-tube olfactometer evaluated the repellent effectiveness of the oils. Lemongrass and beach vitex had slightly attractive characteristics, while *gelam* and *pandan* oils effectively repelled RPWs. Male and female RPWs responded differently: Males were more attracted to lemongrass and beach vitex, while females were more repulsed by *gelam* and *pandan*. These findings suggest that essential oils' insecticidal properties could help develop gender-specific and sustainable agricultural pest management plans.

Keywords: Botanical insecticide, *Rhynchophorus ferrugineus,* phytochemical, feeding deterrent, repellent.

Introduction

Half of the one million bug species are plant-eating insects (Wu & Baldwin, 2010). Millions of ringgits are wasted annually in agriculture due to these pests; thus, when it comes to natural and planted crops, this can have a significant ecological and economic impact. One such pest is the red palm weevil (RPW), scientific name *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae). It is a significant invasive tissue borer with a vast host range restricted to palm trees, infesting roughly 17 palm species globally, including oil palm and coconut. According to Wahizatul *et al.* (2013), the importation of illegal date palm trees in 2007 is what led to the invasion of RPW, particularly in Malaysia. In Malaysia, tracking of the RPW population began in Terengganu state in 2011 and spread quickly to the rest of Peninsular Malaysia within a decade (Yan *et al.*, 2021). During the initial stages of an infestation, it can be extremely difficult to locate the RPW. The most formidable threat is an unseen adversary that inflicts damage from within, leading to the demise of the palm tree within six to eight months. Once the palm is affected, its survival becomes unattainable. By the time the presence of the weevil is identified, it is often too late to intervene and save the palm.

The current integrated pest management (IPM) for RPW in Malaysia heavily relies on chemicals (Malaysian Department of Agriculture, 2017). For example, chemical insecticides such as Spirotetramat, Fipronil, Chlorpyrifos, and Methidathion can be applied to RPW-infested palms using the trunk injection method (Shar *et al.*, 2012) or by spraying cypermethrin on their canopy for some shorter palm plants (Wahizatul *et al.*, 2017). While using chemical or synthetic insecticides can cause an almost complete removal of the pests from the infested area, they negatively influence the natural environment and human health (Chowański *et al.*, 2014). These insecticides can deteriorate ecosystems and human health due to their high toxicity and persistence properties. Thus, the overuse of synthetic insecticides has been a matter of concern for both scientists and the public in recent years. To reduce negative impacts on the environment and human health, natural products with insecticidal characteristics are an excellent alternative to synthetic insecticides. Plant volatiles are essential in communication between host plants and herbivorous insects (Zu *et al.*, 2023). Plants also have built-in defence mechanisms against herbivores and undesirable pests in the form of secondary metabolites known as essential oils (EOs). Over the years, EOs have been popular as insecticides since they are safe for humans and the environment, they have low persistence under field conditions, tend to be relatively nontoxic to non-target subjects, leave little or no residues on food are durable in use as the target pests are less likely to evolve resistance, and they are inexpensive (Isman, 2020).

EOs have been proven by many researchers to exhibit insecticidal activities such as repellency, contact toxicity, ovicidal, larvicidal, and antifeedant against important pests. EOs can easily enter an insect's respiratory system due to their highly volatile nature. EOs can also interact with many different olfactory receptor systems of insects, eliciting various physiological responses (Luker *et al.*, 2023). To name a few, cinnamon's EO exhibits repellent activity against the rice weevil (Shi *et al.*, 2022), while basil oil showed the strongest contact toxicity effect on the third instar larvae of the tobacco cutworm compared to the other 27 EOs studied by Kim *et al.* (2021). On the other hand, EO from plants of the Lamiaceae family showed excellent larvicidal and adulticidal activities against the West Nile virus vector, *Culex pipiens* (El-Kasim Bosly, 2022). In a study by Valcárcel *et al.* (2021) on 14 aromatic plants' EOs against ticks, they identified that the EOs can be grouped into two based on their antifeedant effectiveness: Strong and moderate. They also conclude that the bioactive compounds within the EOs can exert the effect individually or synergistically. There were also studies done on the impact of botanical EOs on RPW. A survey by Mady *et al.* (2021) showed that 10% sweet marjoram EO can kill 50% of the population of RPW larvae, pupa, and adults within 96 hours, 48 hours, and 12 hours, respectively. Aziza and Mona (2016) reported that EO from *Juniperus communis* possesses contact and fumigant toxicity in all stages of RPW especially the eggs and larvae while inducing some biochemical changes in adults when used as contact poison. In addition, Ali *et al.* (2019) tested five different plant EOs, lemon, orange, basil, castor, and eucalyptus and concluded that they could control RPW in the egg and larva stage. Alternatively, *Syzygium aromaticum* and *Cinnamomum eucalyptus* oil revealed an oviposition deterrent effect against RPW (Saad, 2017). The antifeedant effect of eight EO derivatives was also evaluated against RPW larval stages by Yan *et al.* (2021).

The efficiency of the plant EOs as natural insecticides can be credited to their phytochemical composition, particularly the presence of high levels of phenolics and flavonoids. Benelli *et al.* (2018) reported that EOs obtained from the industrial hemp, *Cannabis sativa* dominated by monoterpenes and sesquiterpenes showed strong toxic effects against the housefly, *Musca domestica*. The presence of high levels of phenolic compounds in the Arabic gum tree, *Acacia nilotica* has also been implicated in the toxicity activity of this plant against tobacco cutworms (Gautam *et al.*, 2021). In addition, fruit extract of the cow's udder, *Solanum mammosum* which contains various phytochemicals including phenolics and flavonoids was found to be more effective in the suppression of fruit fly's pupae eclosion than a commercial insecticide (Tran *et al.*, 2022).

In our study, RPWs were treated with EOs from four plants namely *Cymbopogon citratus* (lemongrass), *Melaleuca cajuputi* (gelam), *Vitex rotundifolia* (beach vitex), and *Pandanus amaryllifolius* (pandan) to determine the potential of these EOs as antifeedant and repellency agents for sustainable RPW control. While Malaysians widely use lemongrass and *pandan* as insecticides, the use and study of the insecticidal characteristics of beach vitex and *gelam* are few. In addition, since EOs represent a complex and unique mixture of compounds specific to each plant and extraction procedure, it opens up vast opportunities for researchers to study their insecticidal activities and develop the best formulation for bioinsecticide against the targeted pest.

Materials and Methods

Collection and Rearing of RPWs

The pheromone mass trapping of RPWs was done according to the method by Yan *et al.* (2021) with slight modifications. Pheromone traps were installed around infested areas in Kuala Nerus, Terengganu (5º22'17.6" N 103º04'52.5" E). Sampling sessions were conducted for three months, from June to November 2021. A designated 5 L polypropylene bucket with four holes on its upper part and a cover lid with hanging rope to hang the pheromone lure (Ferrolure P028+, ChemTica Int., Costa Rica) was used. Pineapple slices and water were placed into bucket traps to synergise the trapping effectiveness. Food baits and water levels were replenished each week. At the same time, trapped RPWs were collected and transferred to the Ecology Lab, Universiti Malaysia Terengganu (UMT) for the rearing process.

The collected adult RPWs were reared under in vitro conditions using a ventilated plastic container and sugarcane slices were provided as a food source. A seven-day acclimatisation process at room temperature was taken, which allows adult RPWs to be accustomed to a new food source and environment before conducting a bioassay. Each RPW was examined for sex, physical condition, and behaviour. Gender can be determined by which male RPW has a brush rostrum and which female RPW has a slender rostrum. To get a reliable and accurate reading, RPWs with broken limbs (such as legs, antennae, or rostrum) or that were weak (moving or dying slowly) were not included in the bioassay. Selected test subjects were individually quarantined and starved for 24 hours. Each treatment was replicated three times, consisting of 10 adult RPWs with five males and five females.

Extraction of Essential Oils

Four plants selected in this study are *C. citratus* (lemongrass), *M. cajuputi* (gelam), *V. rotundifolia* (beach vitex), and *P. amaryllifolius* (pandan), while all these plants were obtainable in Kuala Nerus, Terengganu, Malaysia. Lemongrass and *pandan* were purchased from local markets, Suraya Grocery (5°23'45.3" N 103°05'38.3" E) and Pasar Nelayan (5°26'06.2" N 103°03'52.3" E), respectively. Wild *gelam* leaves and beach vitex leaves were collected from the *Melaleuca* forest in Bari Besar, Permaisuri, Terengganu, Malaysia (5°33'14.6" N 102°52'15.8" E) and the beach side of Tok Jembal Beach, Terengganu, Malaysia (5°24'19.0" N 103°05'52.1" E), respectively.

To extract the essential oils (EOs) from the plant samples, they were first washed and cut into smaller pieces to remove unnecessary objects and parts. Extraction of EOs was done using a hydro distillation process with hexane as the solvent. Distilled water was first filled to cover plant samples in the heating mantle. Liquid from the distillate was further processed with hexane in a separatory funnel, where separation of water and oil was formed. All the above procedures were repeated until sufficient EOs were obtained for bioassays. The collected EOs were stored in a glass vial and kept inside the refrigerator before analyses.

Quantification of Total Phenolic and Flavonoid Contents of EO

Total phenolic content (TPC) and total flavonoid content (TFC) for all four extracted plant EOs were determined using the Varian UV-Vis Spectrophotometer CARY 50 CONC, aided by the software CaryWinUV Concentration Application Ver 5.0.0.999 (Agilent Technologies Inc.). All EO test samples and standards (gallic acid and quercetin) were performed in triplicate.

TPC was estimated using Folin-Ciocalteu's method according to Kamboj *et al.* (2015) with some modifications. One mL of the EO test sample was mixed into a test tube containing one mL of 10% Folin-Ciocalteu reagent. Two mL of 7.5% sodium carbonate were added to the test tube and shaken gently. The mixture was then incubated in a dark place for 90 minutes at room temperature until an intense blue colour developed. Then, the absorbance of the sample was measured at 750 nm. The spectrophotometric blank unit was performed using a reagent blank with solvent. Gallic acid (i.e., 0.001, 0.01, 0.02, 0.04, and 0.06 mg/mL) was used as standard. TPC was expressed as mg of gallic acid equivalent (GAE) per gram of plant.

TFC was estimated using an aluminium chloride colourimetric assay (Dowd, 1959) with some modifications. Two mL of EO test sample was mixed with two mL of 2% aluminium chloride. Then, the test tube was shaken gently. The mixture was stored in a dark place for 60 minutes at room temperature until a yellow colour was developed. The absorbance was then measured at 430 nm. The spectrophotometer blank unit was performed using a reagent blank with solvent. Quercetin (i.e., 0.001, 0.01, 0.02, 0.04, and 0.06 mg/mL) was used as standard. TFC was expressed as mg of quercetin equivalent (QE) per gram of plant.

Antifeedant Bioassay of Essential Oils Against Red Palm Weevil

For the antifeedant bioassay, all four extracted plant EOs were first diluted into concentrations of 5% and 10% solution with distilled water and 2% Triton X-100 as an emulsifier. An aqueous solution with the same solvent and emulsifier was the positive control. Antifeedant bioassay for plant EOs against adult RPW was evaluated using the prick-marks counting method. The fresh sugarcane stem was split into two equal longitudinal halves, each with an exposed surface area of about 20.15 cm^2, with a rectangular dimension of 8.5 cm × 2 cm and approximately 1.57 cm^2 for each semicircle side. Each sugarcane slice was treated with (approximately 0.8 mL) EO or control solution by dropper on its exposed surface. The treated sugarcane slice was then transferred into a ventilated plastic container (10 cm diameter x 5 cm height) for evaporation. A pair of adult RPW of different sexes were moved into the container with treated sugarcane slices. The container was then covered tightly using a transparent lid. Observations on feeding were taken for five days. Prick marks on the sugarcane were counted and recorded every 24 hour, and RPW condition was observed. The counting was aided by a square window of 2 × 2 cm^2.

Repellent Bioassay of Essential Oils Against Red Palm Weevil

A repellent bioassay of the EOs was carried out using a Y-tube olfactometer (Figure 1) according to the fabrication by Haris-Hussain *et al.* (2020). Chambers for EO samples and control were designated with a 3 mm transparent Perspex cube in dimensions of 20 x 20 x 20 cm^3 and the top base was an openable lid. An approximate 3 cm round hole was drilled in the middle of one lateral face of the cube. For the two chambers used to place treatment or control, three 15 cm length rectangular holes were designed (oppositely facing the round hole opening side) to allow a single airflow direction from small axial flow fans (wind speed: Approximately 6 ms^{-1}). Rubber rims were used at the end of both arms of the Y-tube to connect the chambers.

The study tested four treatments: Lemongrass, *gelam*, beach vitex, and *pandan*

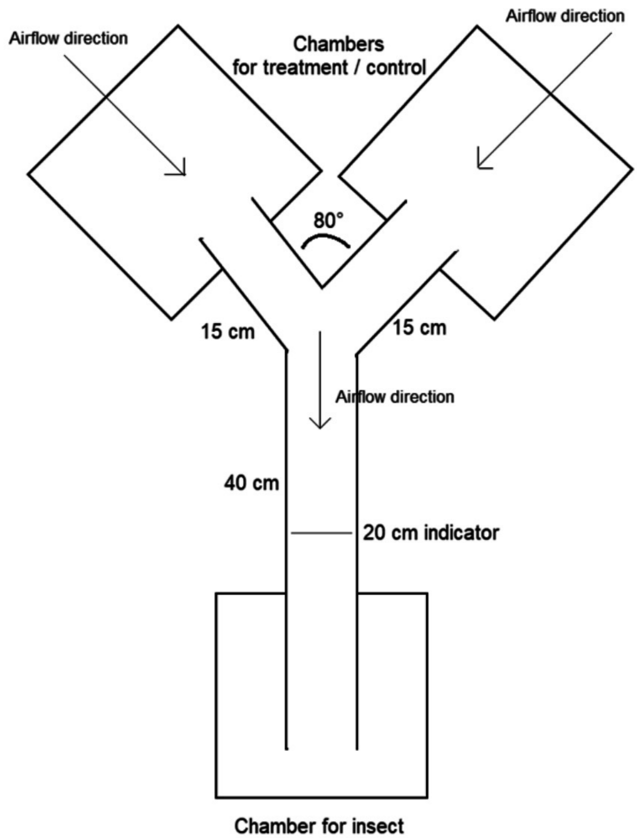

Figure 1: The Y-tube olfactometer for repellent bioassay

EO at a concentration of 10%. The positive control used contains the solvent with 2% Triton X-100. Three hundred grams of sugarcanes were dipped with EO treatments or control (~7 mL) and then placed into the treatment chambers for the evaporation process for about one minute. 10 mL of EO solution or control in an uncovered glass vial was put into each chamber according to the same treatment the sugarcane had previously dipped.

Adult RPWs were acclimated and starved for one day before conducting the bioassay. One adult RPW was placed in the terminal end of the olfactometer. Time was counted once the RPW passed through the indicator line plotted in the terminal tube (Figure 1). Bioassay would be stopped if the RPW entered one of the branch arms and stayed for 1 minute, while motionless RPW for 15 minutes was recorded as a "no-choice" category. Data was not recorded if the RPW did not move or pass through the indicator line for 15 minutes. One hundred adult RPWs (50 males and 50 females) were used for each treatment and the tested subjects were not used repeatedly. The tube or chambers were rotated/side-switched frequently during the bioassay to obtain accurate data. After each assay, all chambers and the tube were washed and rinsed with alcohol before conducting the next treatment.

The average intensity of reaction (IR) was then calculated according to this formula: % IR = [(T - C)/(T + C)]*100, where T is the number of RPW in the chamber containing the EOs and C is the number of RPW observed in the chamber containing the control (Sharaby & Al-Dosary, 2014). Percentage of IR ranging between 1% and 10% indicates that the oils are weakly attractive, 11% and 20% are attractive, and greater than 40% are highly attractive. If less than 1% of the oils are considered repellent (Sharaby & Al-Dosary, 2014).

Statistical Analyses

Data analyses were done using the statistical program IBM SPSS Statistics version 20. TPC and TFC of each plant EO and prick-marks counting data were analysed by mean values from three replications in each treatment. Data was collected only if the RPW had survived more than two days. The comparison of TPC, TFC, and control to each treatment in different concentrations and each day was calculated through one-way ANOVA, followed by Tukey's HSD post hoc test with a significant difference level at $\alpha = 0.05$.

Results and Discussions

Some plants possessed compounds that were repulsive to insects and had an offensive smell. For example, essential oils (EOs) are highly concentrated aromatic compounds extracted from plants. They are volatile and are often referred to as the "essence" of the plant from which they are derived. These substances play a significant part in plant defence against many pest species (Pavela & Benelli, 2016). EOs are made up of different chemical combinations. The phenolic and flavonoid compounds are important because they are made as secondary metabolites when a defence mechanism against phytophagous insects is activated. The total phenolic content (TPC) and flavonoid content (TFC) of the four plant essential oils (EOs) are listed in Table 1. TPC and TFC concentrations in *gelam* are substantially greater than those in the other three EOs ($p < 0.05$). Lemongrass and beach vitex came in second and third, respectively, while *pandan* displayed the lowest value.

Evolutionary processes may have an impact on plant phenolic and flavonoid concentrations. As a part of their defence systems against viruses, herbivores, or environmental stressors, plants have evolved to create these substances (Kumar *et al.*, 2020; Chowdhary *et al.*, 2022). The production of phenolics and flavonoids in plants can be influenced by environmental factors such as soil composition, temperature, light intensity, and the availability of nutrients and water (Yang *et al.*, 2018). Thus, different plant species that belong to the same genus may adopt special and distinctive compositions in various circumstances or locations (Ali & Neda, 2011). For example, in this study, TPC from *gelam* was found to be lower than in other studies from Malaysia, which were conducted in the states of Kedah (37 0.05 GAE/mg extract dry weight) and Kelantan (16.53 0.00 mg/GAE/g) (Noor *et al.*, 2021). In comparison to the findings of Mirghani *et al.* (2012), TPC and TFC in lemongrass EO were marginally lower. *Pandan* EOs from Kedah, Selangor, and Johor states in Malaysia were also determined; however, there was no report for TPC and TFC values in the study (Zakaria *et al.*, 2020).

Among the TPC and TFCs, carvacrol, linalool, alpha-pinene, menthol, cinnamaldehyde, eugenol, 1-8 cineole, geraniol, and limonene are some of the components of EOs that have shown insecticidal activity against different

Table 1: Total phenolic and flavonoid content for the four plant's essential oils

Plant Essential Oil	Total Phenolic Content (mg GAE/g)	Total Flavonoid Content (mg QE/g)
Lemongrass	5.2 ± 0.68^{b}	0.6 ± 0.05^{b}
Gelam	12.3 ± 0.3^{6}a	10.8 ± 0.0^{3}a
Beach vitex	3.4 ± 0.30^{b}	0.4 ± 0.10^{b}
Pandan	1.2 ± 0.45^{c}	0.3 ± 0.0^{6}b

*Different alphabet after the value indicates a statistically significant difference ($n = 3$, $p < 0.05$) among the essential oils with similar phytochemicals content pests (Regnault-Roger *et al.*, 2012; de Oliveira *et al.*, 2014; Singh *et al.*, 2021). According to Moustafa *et al.* (2021), the main compounds of lemongrass leaf EO were α-citral, β-citral, 5-octyldihydro-2(3H)-furanone, nerylacetal, and trans-verbenol. In particular, Citral is considered the key contributor to the insecticidal properties of lemongrass EO (Solomon *et al.*, 2012; Eden *et al.*, 2020). The highest chemical compounds found in *gelam* leaves were caryophyllene, α-terpinolene, α-humulene, β-elemene, and γ-terpinene (Sharif *et al.*, 2019). Casticin is the major flavonoid found in the beach vitex which has many health benefits. In addition, caustic acid, vanillic acid, and 4-hydroxybenzoic acid are some of the phenolic compounds in beach vitex (Azizul *et al.*, 2021). *Pandan*, on the other hand, consists mainly of pyranone; coumarins; 1,4-di-tert-butylphenol; pinane; ethyl palmitate; 3,6,6-trimethyl-1-(1-phtalazinyl)-1,5,6,7-tetrahydro-4H-indazol-4-one; phytol; purpurogallin; squalene; and, decamethyltetrasiloxane (Zakaria *et al.*, 2020).

Table 2 shows the number of prick marks produced by the RPWs after the treatment with the EOs. The long rostrum of the RPW creates prick marks to feed on the substrate or host plant. Therefore, their quantity indicates how much the RPW directly consumed its meal. By making the treated materials unappealing or undesirable, EOs can prevent or disrupt RPW feeding, causing the weevils to remain there for an extended time before starving to death (Talukder *et al.*, 2004; Yappalla *et al.*, 2012). Based on the findings, the plant EOs can be ranked in order of efficacy as follows: Lemongrass > *gelam* > beach vitex. On the other hand, *pandan* did not show any antifeedant effect on the RPW (Table 2). Lemongrass EO

Table 2: Mean number of prick marks recorded for five days after treatments with essential oils from four plants compared to control

Treatment	Day 1	Day 2	Day 3	Day 4	Day 5
Control	5.1 ± 0.68^{b}	10.1 ± 0.82^{b}	16.37 ± 1.39^{b}	22.9 ± 1.59^{b}	28.7 ± 1.80^{b}
5% Lemongrass	2.3 ± 0.40^{a}	5.8 ± 0.96^{a}	11.3 ± 1.90^{ab}	16.5 ± 2.19^{a}	18.7 ± 2.18^{a}
10% Lemongrass	2.4 ± 0.44^{a}	6.1 ± 1.07^{a}	9.4 ± 1.28^{a}	14.5 ± 1.64^{a}	17.9 ± 1.8^{a}
	$F = 9.26$; $p < 0.05$	$F = 6.35$; $p < 0.05$	$F = 5.47$; $p = 0.008$	$F = 5.95$; $p = 0.005$	$F = 9.77$; $p < 0.05$
Control	5.1 ± 0.68^{b}	10.1 ± 0.82^{b}	16.37 ± 1.39^{b}	22.9 ± 1.59^{b}	28.7 ± 1.80^{b}
5% *Gelam*	2.6 ± 0.40^{a}	7.1 ± 1.33^{ab}	12.3 ± 1.99^{a}	19.0 ± 2.63^{a}	21.5 ± 2.70^{a}
10% *Gelam*	0.9 ± 0.32^{a}	6.1 ± 1.15^{a}	12.5 ± 2.33^{a}	19.0 ± 3.29^{a}	24.2 ± 4.28^{a}
	$F = 18.21$; $p < 0.05$	$F = 3.54$; $p = 0.038$	$F = 1.45$; $p = 0.246$	$F = 0.83$; $p = 0.442$	$F = 1.53$; $p = 0.23$
Control	5.1 ± 0.68^{b}	10.1 ± 0.82^{b}	16.37 ± 1.39^{b}	22.9 ± 1.59^{b}	28.7 ± 1.80^{b}
5% Vitex	3.6 ± 0.64^{ab}	8.6 ± 0.97^{ab}	14.8 ± 1.70^{a}	22.4 ± 1.83^{a}	25.9 ± 1.63^{a}
10% Vitex	1.5 ± 0.26^{a}	6.2 ± 1.06^{a}	13.5 ± 2.08^{a}	23.1 ± 2.90^{a}	27.0 ± 3.03^{a}
	$F = 8.02$; $p = 0.001$	$F = 4.30$; $p = 0.02$	$F = 0.70$; $p = 0.505$	$F = 0.28$; $p = 0.972$	$F = 0.42$; $p = 0.661$
Control	5.1 ± 0.68^{b}	10.1 ± 0.82^{b}	16.37 ± 1.39^{b}	22.9 ± 1.59^{b}	28.7 ± 1.80^{b}
5% *Pandan*	3.5 ± 0.5^{5}a	6.7 ± 0.86^{a}	11.2 ± 0.87^{a}	18.2 ± 0.95^{a}	23.5 ± 1.26^{a}
10% *Pandan*	3.97 ± 0.7^{3}a	8.7 ± 1.53^{a}	13.9 ± 1.66^{ab}	19.8 ± 2.58^{a}	25.9 ± 3.67^{a}
	$F = 1.56$; $p = 0.221$	$F = 2.42$; $p = 0.102$	$F = 3.73$; $p = 0.032$	$F = 1.81$; $p = 0.176$	$F = 1.22$; $p = 0.306$

*Different alphabet indicates statistically significant differences ($p < 0.05$) among each group was proven in many studies to have the highest efficacy in terms of antifeedant among other EOs. For example, lemongrass EO showed the highest feeding deterrent activity against various agricultural insect pests, including *Agrotis ipsilon*, *Callosobruchus maculatus*, *Sitophilus granarius*, and *Phthorimaea operculella* (de Souza Alves *et al.*, 2019; Plata-Rueda *et al.*, 2020; Moustafa *et al.*, 2021). A study by Ibrahim *et al.* (2017) found that essential oil derived from lemongrass exhibits significantly higher antifeedant activity against the giant apple snail than essential oil from betel.

A study by Roszaini *et al.* (2013) stated that *gelam* EO was one of the good candidates as an antifeedant for termite control. Likewise, *gelam* EO also showed feeding inhibition criteria against the brown rice grasshopper (Mardiningsih & Rohimatun, 2021). However, due to its antibacterial and antioxidant qualities, *gelam* EO was much more well-known in traditional medicines than as an insecticide (Al-Abd *et al.*, 2015). Beach vitex has not been extensively studied for its potential use as an insecticide or antifeedant. However, it is well-known for its antioxidative, antiproliferative, antiaging properties, and potential as a chemo preventive agent (Rani & Sharma, 2013). It can treat gastrointestinal illnesses, headaches, and inflammation (Azizul *et al.*, 2021). However, other species of *Vitex*, for example, *Vitex negundo* L, exhibited antifeeding behaviour against the cotton leafworms (Shewale *et al.*, 2022) and cotton aphids (Jiang *et al.*, 2016). Among the four plants that were chosen, only *pandan* EO did not demonstrate any antifeedant effect as evidenced by the fact that the number of prick marks on sugarcanes treated with it (either 5% or 10%) did not significantly decrease from the control treatment (Table 2). However, *pandan* has been proven to possess other insecticidal activities such as larvicidal (Mohamad *et al.*, 2021) and deterrent (Ahmad *et al.*, 1995) on other insect species.

The wore-off antifeedant effect of *gelam* and beach vitex EO during the third day (Table 2) was a concern, possibly because EOs were completely volatilised or adult RPWs adapted themselves toward EOs through a detoxifying mechanism after feeding on it. Theoretically, a dwindling effect over time and concentration should be expected. In the vapour phase, EO was vaporised slowly by an air current in a ventilated condition and it could not control the volatile properties of EO (Govere *et al.*, 2000; Oyedele *et al.*, 2002). However, the vapour phase EO can still perform the function in a different mode of action, where gustatory approaches switch to odour modulation (Lee, 2018). Next, RPW is believed to degrade these EOs through detoxification internally. AlJabr *et al.* (2017) revealed that cytochrome P450, glutathione S-transferase and esterase in RPW can detect and break down EOs to a lower-level toxic material. Thus, the RPWs were competent to feed on *gelam* and beach vitex EOs. Further investigation such as odour disruption and RPW detoxification methods should be conducted to understand this issue better.

Table 3 shows the number of RPWs that responded to the chamber and the intensity of reaction (% IR) of the four EOs studied. In general, of the four EOs, *gelam* and *pandan* can be considered repellent against RPW with a < 1% IR. Lemongrass and beach vitex, on the other hand are weakly attractive (i.e., IR between 1% and 10%). According to Bedini *et al.* (2019) as cited in Zeni *et al.* (2021), an EO may have attractant, repellent, or toxic properties dose-dependently. In addition, the shifting of EO's properties from attractant to repellent and finally toxic can be influenced by the species being treated, the EO's composition as well as the EO's concentration (Zeni *et al.*, 2021). Insects such as RPW have highly developed olfactory systems that allow for the detection of and reactions to a variety of volatile cues in the environment. Volatile chemical or odorant detection that results in a certain behaviour mostly entails the reception of odorants in peripheral areas, signal processing in the antennal lobes, and additional processing in the brain (Pellegrino & Nakagawa, 2009; Leal, 2013). Thus, the effects of repellents and attractants in insects depend on how the sensory system detects and processes

Table 3: Percentage intensity of reaction (% IR) of 10% essential oils against the red palm weevil (n = 100)

Essential Oil	**Percentage Intensity of Reaction (%)**					
	Male		**Female**		**Both**	
Lemongrass	8.3	Weakly attractive	-2.2	Repellent	3.2	Weakly attractive
Gelam	-13.0	Repellent	-20.0	Repellent	-16.0	Repellent
Beach vitex	13.6	Attractive	-2.0	Repellent	5.4	Weakly attractive
Pandan	-10.0	Repellent	9.1	Weakly attractive	0.0	Repellent

odour components, with olfactory receptors and neurons being the primary level of interaction (Verschut *et al.*, 2019).

In a study conducted on sweet potato weevils, Samantaray and Korada (2016) observed that some compounds such as cis-3-hexen-1-ol, consistently elicited high axonal action potentials within the olfactory receptors of both genders, while cis-3-hexanal and α-humulene elicited the highest potentials in female antennal receptors relative to male weevils. These compounds exhibited a repellent behaviour, resulting in the reduced attraction of weevils. This indicates that α-humulene is one of the key chemical constituents found in *gelam* (Sharif *et al.*, 2019), the repellent behaviour of RPWs as shown in Table 3. On the other hand, *pandan* leaves were the most effective in repelling rice weevils, *S. oryzae* with a repellency percentage of 47% among other plants studied (Mohd Arafah *et al.*, 2023).

Gender wise, the female RPWs reacted negatively to three of the four EOs studied (Table 3). Contrastingly, the male RPWs were attracted to lemongrass and beach vitex EOs but were repelled by *gelam* and *pandan* EOs. The differences in the behaviour between the male and female RPWs observed may be due to several factors. Male and female insects can possess differences in their sensory organs. For example, male RPWs have reddish-brown hairs on their elongated snout or rostrum, while females have no hairs and are longer, slender, and slightly downward-curvature (Abdel-Banat & El-Shafie, 2023). The differences in olfactory receptors or sensitivity might lead to varying responses to volatile repellents. In addition, it is also possible that male and female weevils have distinct nutritional requirements, which could affect how they react to essential oils. In contrast to females, which may have varied preferences due to their particular requirements during egg-laying or the development of progeny, males may be more drawn to or repelled by certain plant compounds that supply vital nutrients for their reproductive activities (Genç, 2006; Wu *et al.*, 2020; Huck *et al.*, 2021). The physiology and genetic makeup of male and female weevils differ, which has an impact on behaviour. These discrepancies may be caused by different hormone levels (Nijhout & Laub, 2018) or the expression of specific genes (Weitekamp *et al.*, 2017). As a result, compared to females, the EOs may cause different physiological or neurological reactions in males, resulting in divergent behaviours (Krzyżowski *et al.*, 2020).

EOs that are considered attractants can also be beneficial in sustainable pest management. The attractive EOs can be employed in conjunction with the biological control agents. They can attract pests into an area where natural predators have been released (Liu *et al.*, 2019). Certain EOs have an appealing quality that attracts insects who use them as aggregation signals. For example, α-copaene, a minor component in the EOs of various plant species is a potent attractant for the male Mediterranean fruit flies, *Ceratitis capitata* and potentially serves as a chemical cue for the female flies to aggregate with the male flies during mating (Nishida *et al*., 2000). Furthermore, an environmentally friendly method of pest control can be achieved by reducing the total reliance on chemical pesticides through the use of attractants in pest management.

As stated earlier, phenolic and flavonoid compounds play an important role in the insecticidal activities of EOs. The phenolic compounds from EO are believed to play a crucial role in chemical defence mechanisms, as they often carry out antifeeding, digestibility-reducing, and other effects on herbivores or insects (Rehman *et al*., 2012; Pratyusha, 2022). In this study, *gelam* EO contained the highest amount of TPC and TFC (Table 1), yet it was not the most effective EO in reducing the consumption rate of adult RPWs. Contrastingly, *pandan* oil with the lowest TPC and TFC content (Table 1) showed a repellent activity against the male RPWs but no antifeedant activity. Perhaps not surprisingly, while containing a high amount of phenolic compounds, a certain chemical constituent is the most important part that plays a role in the defence against a specific pest. For example, citral and genaryl acetate from lemongrass EO caused toxic and repellent effects on *Anticarsia gemmatalis* (Brügger *et al*., 2021). Filiferol, on the other hand, was found to be involved in defence against *Rhynchophorus ferrugineus* in *Washingtonia filifera* palm (Cangelosi *et al*., 2015). These studies pointed out that the defence mechanism of an insect often took effects from a specific chemical compound but not the overall amount of phenolic compounds. In addition, *pandan* EO contains some compounds that insects find repellent, but possibly in lower concentrations or different types than those in *gelam*, lemongrass and beach vitex. Therefore, it was insufficient to correlate the TPC and TFC of EO with its antifeedant and repellent properties; nonetheless, these values were still significant for recording and determining other bioactivities.

Conclusions

This study offers strong proof of the effectiveness of EOs obtained from lemongrass (*C. citratus*), *gelam* (*M. cajuputi*), beach vitex (*V. rotundifolia*), and *pandan* (*P. amaryllifolius*) as possible bioinsecticides against the invasive RPW. The results show that these natural oils have different levels of antifeedant and repellent properties, which are important for creating environmentally friendly pest management strategies. With the highest concentrations of phenolics and flavonoids, *gelam* oil stood out and may have significant insecticidal potential. It demonstrated notable repulsive qualities against RPWs, as did *pandan* oil. On the other hand, lemongrass oil showed the strongest antifeedant efficacy but with a noticeably reduced repelling impact. The study also found that different genders responded differently to these oils, underscoring the significance of considering gender when developing pest management plans. Except for *pandan*, female RPWs were generally more vulnerable to the repelling properties of the oils, whereas male RPWs exhibited clear preferences being drawn to beach vitex and lemongrass but repulsed by *gelam* and *pandan*.

These results provide insightful information for the agriculture industry, especially in areas with problematic RPW infestations. These EOs provide an eco-friendly substitute for traditional chemical pesticides, supporting the larger goals of sustainable agriculture and natural resource management. Subsequent investigations may build upon these results by investigating the molecular underpinnings of these oils' insecticidal characteristics and evaluating their usefulness in real-world settings. This study also highlights the potential of natural resources in resolving agricultural difficulties and adds to the expanding body of knowledge supporting the use of chemicals derived from plants in integrated pest management.

Acknowledgements

The authors acknowledge the Ministry of Higher Education of Malaysia for providing the funds under the Fundamental Research Grant Scheme (Project Code: FRGS/1/2019/STG04/UMT/02/1) and the Research Management Office at Universiti Malaysia Terengganu (UMT) for managing the fund. The authors also acknowledge the Faculty of Science and Marine Environment and the Centre of Research and Field Service, UMT, for providing the lab facilities.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

References

Abdel-Banat, B. M. A., & El-Shafie, H.A.F. (2023). Management of the red palm weevil in date palm plantations in Al-Ahsa Oasis of Saudi Arabia. *Plant Health Cases.* https://doi.org/10.1079/planthealthcases.2023.0001

Ahmad, F. B., Mackeen, M. M., Ali, A. M., Mashirun, S. R., & Yaacob, M. M. (1995). Repellency of essential oils against the domiciliary cockroach, *Periplaneta americana*. *International Journal of Tropical Insect Science, 16*(3-4), 391-393.

Al-Abd, N. M., Mohamed Nor, Z., Mansor, M., Azhar, F., Hasan, M. S., & Kassim, M. (2015). Antioxidant, antibacterial activity, and phytochemical characterization of *Melaleuca cajuputi* extract. *BMC Complementary and Alternative Medicine, 15*(1), 1-13.

Ali, G., & Neda, G. (2011). Flavonoids and phenolic acids: Role and biochemical activity in plants and human. *Journal of Medicinal Plants Research, 5*(31), 6697-6703.

Ali, M. A., Mohanny, K. M., Mohamed, G. S., & Allam, R. O. H. (2019). Efficacy of some promising plant essential oils to control the red palm weevil *Rhynchophorus ferrugineus* Olivier (Coleoptera: Curculionidae) under laboratory conditions. *SVU-International Journal of Agricultural Sciences, 1*(2), 12-45.

AlJabr, A. M., Hussain, A., Rizwan-ul-Haq, M., & Al-Ayedh, H. (2017). Toxicity of plant secondary metabolites modulating detoxification genes expression for natural red palm weevil insecticide development. *Molecules, 22*(1), 169.

Aziza, S., & Mona, E. D. (2016). Toxic and biochemical effects of *Juniperus communis* essential oil on the red palm weevil *Rhynchophorus ferrugineus* (Olivier.) (Coleoptera: Curculionidae). *Egyptian Journal of Biological Pest Control, 26*(2), 339.

Azizul, N. H., Ahmad, W. A. N. W., Rosli, N. L., Azmi, M. A. H. M., Liang, C. E., Mazlan, N. W., & Assaw, S. J. T. M. R. (2021). The coastal medicinal plant *Vitex rotundifolia*: A mini-review on its bioactive compounds and pharmacological activity. *Traditional Medicine Research, 6*(2), 11.

Benelli, G., Pavela, R., Petrelli, R., Cappellacci, L., Santini, G., Fiorini, D., Sut, S., Dall'Acqua, S., Canale, A., & Maggi, F. (2018). The essential oil from industrial hemp (*Cannabis sativa* L.) by-products as an effective tool for insect pest management in organic crops. *Industrial Crops and Products, 122*, 308-315.

Brügger, B. P., Plata-Rueda, A., Wilcken, C. F., Souza, L. S. A. D., Serrão, J. E., Carvalho, A. G., Zanuncio, J. C., & Martínez, L. C. (2021). Exposure to lemongrass essential oil and its components causes behavior and respiratory disturbs in *Anticarsia gemmatalis*. *International Journal of Pest Management,* 1-9. https://doi.org/10.1080/09670874.2021.1944700

Cangelosi, B., Clematis, F., Monroy, F., Roversi, P. F., Troiano, R., Curir, P., & Lanzotti, V. (2015). Filiferol, a chalconoid analogue from *Washingtonia filifera* possibly involved in the defence against the red palm weevil *Rhynchophorus ferrugineus* Olivier. *Phytochemistry, 115,* 216-221.

Chowański, S., Kudlewska, M., Marciniak, P. & Rosiński, G. (2014). Synthetic insecticides - Is there an alternative?. *Polish Journal of Environmental Studies, 23*(2), 291-302.

Chowdhary, V., Alooparampil, S., Pandya, R. V., & Tank, J. G. (2022). Physiological function of phenolic compounds in plant defense system. *IntechOpen*. https://doi.org/10.5772/intechopen.101131

de Oliveira, C., Cardoso, M., Figueiredo, A., de Carvalho, M., Miranda, C., Marques Albuquerque, L., Lee Nelson, D., Souza Gomes, M., Silva, L., Andrade Santiago, J., Teixeira, M., & Brandão, R. (2014). Chemical composition and allelopathic activity of the essential oil from *Callistemon viminalis* (Myrtaceae) blossoms on lettuce (*Lactuca sativa* L.) seedlings. *American Journal of Plant Sciences, 5*, 3551-3557. https://doi.org/10.4236/ajps.2014.524371

de Souza Alves, M., Campos, I. M., de Brito, D. D. M. C., Cardoso, C. M., Pontes, E. G., & de Souza, M. A. A. (2019). Efficacy of lemongrass essential oil and citral in controlling *Callosobruchus maculatus* (Coleoptera: Chrysomelidae), a post-harvest cowpea insect pest. *Crop Protection, 119,* 191-196. https://doi.org/10.1016/j.cropro.2019.02.007

Dowd, L. E. (1959). Spectrophotometric determination of quercetin. *Analytical Chemistry, 31*(7), 1184-1187. https://doi.org/10.1021/ac60151a033

Eden, W. T., Alighiri, D., Supardi, K. I., & Cahyono, E. (2020). The mosquito repellent activity of the active component of air freshener gel from Java citronella oil (*Cymbopogon winterianus*). *Journal of Parasitology Research, 2020,* 1-5. https://doi.org/10.1155/2020/9053741

El-Kasem Bosly, H. A. (2022). Larvicidal and adulticidal activity of essential oils from plants of the Lamiaceae family against the West Nile virus vector, *Culex pipiens* (Diptera: Culicidae). *Saudi Journal of Biological Sciences, 29*(8). https://doi.org/10.1016/j.sjbs.2022.103350

Gautam, S., Chimni, S. S., Arora, S., & Sohal, S. K. (2021). Toxic effects of purified phenolic compounds from *Acacia nilotica* against common cutworm. *Toxicon, 203*, 22-29. https://doi.org/10.1016/j.toxicon.2021.09.017

Genç, H. (2006). General principles of insect nutritional ecology. *Trakya University Journal of Natural Science, 7*(1), 53-57.

Govere, J., Durrheim, D. N., Du Toit, N., Hunt, R. H., & Coetzee, M. (2000). Local plants as repellents against *Anopheles arabiensis*, in Mpumalanga Province, South Africa. *The Central African Journal of Medicine, 46*(8), 213-216.

Haris-Hussain, M., Kamarudin, N., & Azmi, W. A. (2020). Efficacy of baits for red palm weevil (RPW), *Rhynchophorus ferrugineus* Olivier under constant laboratory condition. *Journal of Oil Palm Research, 32*(2), 355-364.

Huck, D. T., Klein, M. S., & Meuti, M. E. (2021). Determining the effects of nutrition on the reproductive physiology of male mosquitoes. *Journal of Insect Physiology, 129*(2), 104191. https://doi.org/10.1016/j.jinsphys.2021.104191

Ibrahim, R., Haiyee, Z. A., & Latip, S. N. H. M. (2017). The antifeedant activity of essential oil from *Cymbopogon citratus* and *Piper bitle* for controlling golden apple snail, *Pomacea canaliculata*. *Journal of Fundamental and Applied Sciences, 9*(6S), 39-49. https://doi.org/10.4314/jfas.v9i6s.4

Isman, M. B. (2020). Botanical insecticides in the 21st century - fulfilling their promise?. *Annual Review in Entomology, 65*, 233-

249. https://doi.org/10.1146/annurev- ento-011019-025010

Jiang, E., Zhu, Y., & Wang, J. (2016). Biological effectiveness of extracts from *Vitex negundo* against *Aphis gossypii* (Homoptera: Aphididae). *Acta Entomologica Sinica, 59*(5), 538-545.

Kamboj, A., Gupta, R., Rana, A., & Kaur, R. (2015). Application and analysis of the Folin Ciocalteu method for the determination of the total phenolic content from extracts of *Terminalia bellerica*. *European Journal of Biomedical and Pharmaceutical Sciences, 2*, 201-2015.

Kim, S., Yoon, J., & Tak, J. H. (2021). Synergistic mechanism of insecticidal activity in Basil and Mandarin essential oils against the tobacco cutworm. *Journal of Pest Science, 94,* 1119-1131. https://doi.org/10.1007/s10340-021-01345-8

Krzyżowski, M., Baran, B., Łozowski, B., & Francikowski, J. (2020). The effect of *Rosmarinus officinalis* essential oil fumigation on biochemical, behavioral, and physiological parameters of *Callosobruchus maculatus*. *Insects, 11*(6), 344. https://doi.org/10.3390/insects11060344

Kumar, S., Abedin, M. M., Singh, A. K., & Das, S. (2020). Role of phenolic compounds in plant-defensive mechanisms. In Lone, R., Shuab, R., & Kamili, A. (Eds.), *Plant phenolics in sustainable agriculture*. Springer. https://doi.org/10.1007/978-981-15-4890-1_22

Leal, W. S. (2013). Odorant reception in insects: Roles of receptors, binding proteins, and degrading enzymes. *Annual Review in Entomology, 58*, 373-391.

Lee, M. Y. (2018). Essential oils as repellents against arthropods. *BioMed Research International*, *2018,* 6860271. https://doi.org/10.1155/2018/6860271

Liu, S., Zhao, J., Hamada, C., Cai, W., Khan, M., Zou, Y., & Hua, H. (2019). Identification of attractants from plant essential oils for *Cyrtorhinus lividipennis*, an important predator of rice planthoppers. *Journal of Pest Science*, *92*, 769-780. https://doi.org/10.1007/s10340-018-1054-1

Luker, H. A., Salas, K. R., Esmaeili, D., Holguin, F. O., Bendzus-Mendoza, H., & Hansen, I. A. (2023). Repellent efficacy of 20 essential oils on *Aedes aegypti* mosquitoes and *Ixodes scapularis* ticks in contact-repellency assays. *Scientific Report, 13*, 1705. https://doi.org/10.1038/s41598-023-28820-9

Mady, H. Y., Ahmed, M. M., & El Namaky, A. H. (2021). Efficiency of *Origanum majorana* essential oil as insecticidal agent against *Rhynchophorus ferrugineus* the red palm weevil (Olivier) (Coleoptera: Curculionidae). *Journal of Biopesticides, 14*(1), 32-40.

Malaysian Department of Agriculture. (2017). *Prosedur Operasi Standard (SOP) kawalan perosak kumbang palma (RPW)*. Jabatan Pertanian Malaysia.

Mardiningsih, T. L., & Rohimatun. (2021). Bioactivities of Lamiaceae, Myristicaceae, and Myrtaceae plant oils against *Nilaparvata lugens* Stâl. (Hemiptera: Delphacidae). *IOP Conference Series: Earth and Environmental Science, 948*, 012060. https://doi.org/10.1088/1755-1315/948/1/012060

Mirghani, M. E. S., Liyana, Y., & Parveen, J. (2012). Bioactivity analysis of lemongrass (*Cymbopogan citratus*) essential oil. *International Food Research Journal, 19*(2), 569-575.

Mohamad, N. N., Nathan, M. M., & Amzah, M. A. (2021). Larvicidal activity of *Piper nigrum*, *Pandanus amaryllifolius*, *Cymbopogon nardus*, *Cinnamomum burmanii* and *Azadirachta indica* herbs extracts on *Aedes aegypti* larvae. *MAEH Journal of Environmental Health, 3*(2), 23-26.

Mohd Arafah, N. S., Jun, C. Y., Mohamed Shariff, S. S., Mohd Noor, N. Q. I., & Zaharudin,

N. (2023). Effects of selected plants against rice weevil (*Sitophilus oryzae*). *Malaysian Applied Biology, 52*(4), 113-118. https://doi.org/10.55230/mabjournal.v52i4.d044

Moustafa, M. A., Awad, M., Amer, A., Hassan, N. N., Ibrahim, E. D. S., Ali, H. M., Akrami, M., & Salem, M. Z. (2021). Insecticidal activity of lemongrass essential oil as an eco-friendly agent against the black cutworm *Agrotis ipsilon* (Lepidoptera: Noctuidae). *Insects, 12*(08), 737. https://doi.org/10.3390/insects12080737

Nijhout, H. F., & Laub, E. (2018). The role of hormones. In Córdoba-Aguilar, A., González-Tokman, D., & González-Santoyo, I. (Eds.), *Insect behavior: From mechanisms to ecological and evolutionary consequences.* Oxford Academic. https://doi.org/10.1093/oso/9780198797500.003.0004

Nishida, R., Shelly, T. E., Whittier, T. S., & Kaneshiro, K. Y. (2000). α-Copaene, a potential rendezvous cue for the Mediterranean fruit fly, *Ceratitis Capitata*?. *Journal of Chemical Ecology, 26*, 87-100. https://doi.org/10.1023/A:1005489411397

Noor, A. A. M., Yusuf, S. M., Wahab, W. N. A. W. A., Adam, M. F. I. C., & Sul'ain, M. D. (2021). Evaluation on composition, antioxidant and toxicity of *Melaleuca cajuputi* leaves. *Advances in Traditional Medicine, 21*(4), 693-699. https://doi.org/10.1007/s13596-020-00479-x

Oyedele, A. O., Gbolade, A. A., Sosan, M. B., Adewoyin, F. B., Soyelu, O. L., & Orafidiya, O. O. (2002). Formulation of an effective mosquito-repellent topical product from lemongrass oil. *Phytomedicine, 9*(3), 259-262. https://doi.org/10.1078/0944-7113-00120

Pavela, R., & Benelli, G. (2016). Essential oils as ecofriendly biopesticides? Challenges and constraints. *Trends in Plant Science, 21*(12), 1000-1007. https://doi.org/10.1016/j.tplants.2016.10.005

Pellegrino, M., & Nakagawa, T. (2009). Smelling the difference: Controversial ideas in insect olfaction. *Journal in Experimental Biology, 212*, 1973-1979.

Plata-Rueda, A., Rolim, G. D. S., Wilcken, C. F., Zanuncio, J. C., Serrão, J. E., & Martínez, L. C. (2020). Acute toxicity and sublethal effects of lemongrass essential oil and their components against the Granary weevil, *Sitophilus granarius*. *Insects, 11*(6), 379. https://doi.org/10.3390/insects11060379

Pratyusha, S. (2022). Phenolic compounds in the plant development and defense: An overview. In M., Hasanuzzaman, & K., Nahar (Eds.), *Plant stress physiology - Perspectives in agriculture*. IntechOpen. https://doi.org/10.5772/intechopen.102873

Rani, A., & Sharma, A. (2013). The genus *Vitex*: A review. *Pharmacognosy Review, 7*(14), 188-198. https://doi.org/10.4103/0973-7847.120522

Regnault-Roger, C., Vincent, C., & Arnason, J. T. (2012). Essential oils in insect control: Low-risk products in a high-stakes world. *Annual Review in Entomology, 57*, 405-424. https://doi.org/10.1146/annurev-ento-120710-100554

Rehman, F., Khan, F. A., & Badruddin, S. M. A. (2012). Role of phenolics in plant defense against insect herbivory. In Khemani, L. D., Srivastava, M. M., & Srivastava, S. (Eds.), *Chemistry of phytopotentials: Health, energy and environmental perspectives* (pp. 309-313). Springer.

Roszaini, K., Nor Azah, M. A., Mailina, J., Zaoini, S., & Faridz, Z. M. (2013). Toxicity and antitermite activity of the essential oils from *Cinnamomum camphora*, *Cymbopogon nardus*, *Melaleuca cajuputi* and *Dipterocarpus* sp. against *Coptotermes curvignathus*. *Wood Science and Technology, 47*, 1273-1284. https://doi.org/ 10.1007/s00226-013-0576-1

Saad, M. M. (2017). Oviposition deterrent effect of four essential oils against the date palm weevil, *Rhynchophorus ferrugineus* Olivier. *Middle East Journal of Agriculture Research, 6*(4), 1336-1345.

Samantaray, T., & Korada, R. R. (2016). Electrophysiological and behavioural responses of sweetpotato weevil, *Cylas formicarius* to green leaf volatiles and terpenoids. *Current Science, 110*(5), 902-905. https://doi.org/24907976

Shar, M. U., Rustamani, M. A., Nizamani, S. M., & Bhutto, L. A. (2012). Red palm weevil (*Rhynchophorus ferrugineus* Olivier) infestation and its chemical control in Sindh province of Pakistan. *African Journal or Agricultural Research, 11*, 1666-1673.

Sharaby, A., & Al-Dosary, M. (2014). An electric air flow olfactometer and the olfactory response of *Rhynchophorous ferrugineus* weevil to some volatile compounds. *Journal of Agriculture and Ecology Research International, 1*(1), 40-50.

Sharif, Z. M., Kamal, A. F., & Jalil, N. J. (2019). Chemical composition of *Melaleuca cajuputi* Powell. *International Journal of Engineering and Advanced Technology, 9*(1), 3479-3483.

Shewale, V. S., Khairmode, P. V., Lawand, S. T., Netam, V. S., & Bhosale, A. R. (2022) Antifeedant and insecticidal activity of different solvent extracts of *Vitex negundo* (L) against cotton leafworm *Spodoptera litura* (Fab.). *Asian Journal of Research in Zoology, 5*(4), 32-38.

Shi, W., Yan, R., & Huang, L. (2022). Preparation and insecticidal performance of sustained-release cinnamon essential oil microemulsion. *Journal of the Science of Food and Agriculture, 102*(4), 1397-1404. https://doi.org/10.1002/jsfa.11472

Singh, S., Kaur, I., & Kariyat, R. (2021). The multifunctional roles of polyphenols in plant-herbivore interactions. *International Journal of Molecular Sciences, 22*, 1442. https://doi.org/10.3390/ijms22031442

Solomon, B., Gebre-Mariam, T., & Asres, K. (2012). Mosquito repellent actions of the essential oils of *Cymbopogon citratus*, *Cymbopogon nardus* and *Eucalyptus citriodora*: Evaluation and formulation studies. *Journal of Essential Oil Bearing Plants, 15*(5), 766-773. https://doi.org/10.1080/0972060X.2012.10644118

Talukder, F., Islam, M., Hossain, M., Rahman, M., & Alam, M. (2004). Toxicity effects of botanicals and synthetic insecticides on *Tribolium castaneum* (Herbst) and *Rhyzopertha dominica* (F.). *Bangladesh Journal of Environmental Sciences, 10*(2), 365371.

Tran, T. M., Tang, H. C., Huynh, H. P., Yen D. H. N., Tuan, L. A. P., Kaeko, K., & Tran, D. B. (2022). Evaluation of the insecticidal activity of *Solanum mammosum* (L.) fruit extract against *Drosophila melanogaster*. *Journal of Animal Behaviour and Biometeorology, 10,* 2218. https://doi.org/10.31893/jabb.22018

Valcárcel, F., Olmeda, A. S., González, M. G., Andrés, M. F., Navarro-Rocha, J., & González-Coloma, A. (2021). Acaricidal and insect antifeedant effects of essential oils from selected aromatic plants and their main components. *Frontiers in Agronomy, 3,* 662802. https://doi.org/10.3389/fagro.2021. 662802

Verschut, T. A., Carlsson, M. A., & Hambäck, P. A. (2019). Scaling the interactive effects of attractive and repellent odours for insect search behaviour. *Scientific Reports, 9*(1), 1-8. https://doi.org/10.1038/s41598-019-51834-1

Wahizatul, A. A., Lian, C. J., Zakeri, H. A., Yusuf, N., Omar, W. B. W., Wai, Y. K., & Haris-Hussain, M. (2017). The red palm weevil, *Rhynchophorus ferrugineus*: Current issues and challenges in Malaysia. *Oil Palm Bulletin, 74*, 17-24.

Wahizatul, A. A., Zazali, C., Abdul, R., & Nurul'Izzah, A. G. (2013). A new invasive coconut pest in Malaysia: The red palm weevil (Curculionidae: *Rhynchophorus ferrugineus*). *Planter, 89*(1043), 97-110.

Weitekamp, C. A., Libbrecht, R., & Keller, L. (2017). Genetics and evolution of social behavior in insects. *Annual Review of Genetics, 51,* 219-239. https://doi.org/10.1146/annurev-genet-120116-024515

Wu, J., & Baldwin, I. T. (2010). New insights into plant responses to the attack from insect herbivores. *Annual Review of Genetics, 44,* 1-24. https://doi.org/10.1146/annurev-genet-102209-163500

Wu, Q., Yu, G., Cheng, X., Gao, Y., Fan, X., Yang, D., Xie, M., Wang, T., Piper, M. D. W., & Yang, M. (2020). Sexual dimorphism in the nutritional requirement for adult lifespan in *Drosophila melanogaster*. *Aging Cell, 19*(3), e13120. https://doi.org/10.1111/acel.13120

Yan, T. K., Asari, A., Salleh, S. A., & Wahizatul, A. A. 2021. Eugenol and thymol derivatives as antifeedant agents against red palm weevil, *Rhynchophorus ferrugineus* (Coleoptera: Dryophthoridae) larvae. *Insects, 12*(6), 551. https://doi.org/10.3390/insects12060551

Yang, L., Wen, K. S., Ruan, X., Zhao, Y. X., Wei, F., & Wang, Q. (2018). Response of plant secondary metabolites to environmental factors. *Molecules, 23*(4), 762. https://doi.org/10.3390/molecules23040762

Yappalla, R., Nandagopal, B., & Thimmappa, S. (2012). Botanicals as grain protectants. *Psyche: A Journal of Entomology, 2012*, 646740. https://doi.org/10.1155/2012/646740

Zakaria, M. M., Zaidan, U. H., Shamsi, S., & Abd Gani, S. S. (2020). Chemical composition of essential oils from leaf extract of *pandan*, *Pandanus amaryllifolius* ROXB. *Malaysian Journal of Analytical Sciences, 24*(1), 87-96.

Zeni, V., Benelli, G., Campolo, O., Giunti, G., Palmeri, V., Maggi, F., Rizzo, R., Lo Verde, G., Lucchi, A., & Canale, A. (2021). Toxics or lures? Biological and behavioral effects of plant essential oils on Tephritidae fruit flies. *Molecules, 26*(19), 5898. https://doi.org/10.3390/molecules26195898

Zu, P., Zhang, Y., & Luo, B. (2023). Chemical communication between plants and insects. *Journal of Systematics and Evolution, 61*(3), 441-444. https://doi.org/10.1111/jse.12955