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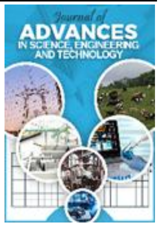

Feeding Deterrence and Insecticidal Activity of Selected Plant Essential Oils Against the Larger Grain Borer *Prostephanus truncatus* in Stored Maize Grains

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ABSTRACT

In our screening program for botanical pesticides from local plants, the powders and essential oils from *Plectranthus marrubioides* (Hochst ex Benth), *Tetradenia riparia* (Hochst Codd), *Ocimum suave* (Wild), *Lippia javanica* (Burm, Spreng), and *Ocimum lamiifollium* (Hochst ex Benth) were found to possess insecticidal activity against the maize weevil, *Prostephanus truncatus*. The essential oils from aerial parts of the plants were obtained by hydro-distillation and tested under laboratory conditions (25 ± 1°C, 70-75% R.H.) for their ability to protect the grains from damage by *P. truncatus*. The insects were reared and tested on whole maize grain (variety DK 8031). Bioassays were conducted using five dilution levels of essential oils in hexane (10, 5, 2.5, 1.25, and 0.625% wt/wt), each tested on ten unsexed adult large grain borers per replicate, with four replicates per treatment. The mortality data of the insects at each level of dilution were collected, and the mean values were computed and subjected to Student-Newman-Keuls (SNK) t-test. Essential oils were also tested as antifeedants of the insect in dried maize. It was observed that within the 0.625% level of dilution, the oil extracts showed a significant difference ($p < 0.05$) in the antifeedant test done using the different plant essential oils. Of the five plant oils, *P. marrubioides* and *T. riparia* showed the highest insecticidal activity with the lowest mean of 0.55 ± 0.15 and 0.40 ± 0.11, respectively, as compared to *O. lamiifolium* (2.4 ± 0.11), O. suave (2.55 ± 0.11), and *L. javanica* (2.5 ± 0.15) after a period of six months. The chemical constituents of the two most potent oils were analyzed by GC-MS. The main compounds in *P. marrubioides* essential oil were δ-2-carene (10.84%), *o*-cymene (8.72%), 1,8-cineole (7.89%), and camphor (5.65%). *T. riparia* essential oil was found to be rich in fenchone (24.74%), β-pinene (5.23%), *o*-cymene (5.16%), and 1,8-cineole (10.89%). These results show that these plant oils, and particularly *P. marrubioides* and *T. riparia,* have the potential to protect dry stored grain products from damage by the larger grain borer. Consequently, the plant oils can be developed into post-harvest control agents of the larger grain borer in stored grain products.

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1. Introduction

The Larger Grain Borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) (Fig. 1) is a serious insect pest of maize (*Zea mays*), cassava (*Manihot esculenta*), wood, and other stored products (Nang'ayo et al., 2002; Quellhorst et al., 2021). *Prostephanus truncatus* is a major post-harvest pest in sub-Saharan Africa, causing estimated maize and dried cassava losses of up to 30–40%, with economic losses ranging from USD 18.2 billion to USD 78.9 million annually between the years 1970 and 2020 (Diagne et al., 2021), depending on infestation levels and control strategies. The latest report on the occurrence of *P. truncatus* in Botswana follows similar reports in neighboring countries, Zambia,

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Namibia, South Africa, and Zimbabwe in 1993, 1998, 1999, and 2005, respectively (Quellhorst et al., 2021). This invasive insect pest was introduced from its native Meso-American region into East Africa through Tanzania in the late 1970s (Dunstan & Magazini, 1981; Farrell & Schulten, 2002; Quellhorst et al., 2021). This devastating insect pest is a biosecurity threat that continues to spread around the world (Quellhorst et al., 2022), having already been recorded in 21 African countries among at least 36 reported territories globally (Quellhorst et al., 2021). Adult *Prostephanus truncatus* attacks maize, creating large and noticeable holes that ultimately 'skeletonize' the grains (Kumar, 2002; Quellhorst et al., 2021) (Fig. 2). Larval *Prostephanus truncatus* feed mainly on the floury endosperm and the germ tissues (Vowotor et al., 1998). *Prostephanus truncatus* is among stored product pests that include the square-necked grain beetle, *Cathartus quadricollis* (Silvanidae), and the maize weevil, *Sitophilus zeamais* (Curculionidae), that have also been reported to facilitate colonization of stored grains by mycotoxigenic fungi such as *Aspergillus* spp. and *Fusarium* spp. that produce aflatoxins and fumonisins (Lamboni & Hell, 2009; Kheseli et al., 2011; Danso et al., 2018). The Larger Grain Borer *Prostephanus truncatus* can cause maize postharvest losses as high as 56.7% within six months of storage and hence is a serious threat to food security and nutrition (Bezabih et al., 2022).

Control of *Prostephanus truncatus* has been a challenge (Quellhorst et al., 2022), and various control options are being considered for Integrated Pest Management (IPM) of this damaging insect pest (Tanda et al., 2022). Biopesticides, especially those based on insecticidal plants (Okwute, 2012; Zoubiri & Baaliouamer, 2014; Riyaz et al., 2022), have been attracting a lot of interest in the management of *P. truncatus* and other stored products pests (Mantzoukas et al., 2020; Gariba et al., 2021; Tanda et al., 2022). Among the main reasons behind the growing interest in insecticidal plants is their affordability and safety to human and animal health, besides not posing adverse effects to non-target biodiversity and the environment (Ponsankar et al., 2016; Riyaz et al., 2022).

Various insecticidal plant species around the world are being investigated for their capacity to control *Prostephanus truncatus* (Bezabih et al., 2022). Such plant species include Horsewood or 'Maggot Killer' (*Clausena anisata*; Rutaceae), Silver Thistle (*Carlina acaulis*; Asteraceae), Lenten Rose (*Helleborus odorus*; Ranunculaceae), and *Equilabium glandulosum* (*Plectranthus glandulosus*; Lamiaceae), which has had nomenclatural disharmonies (Lukhoba et al., 2006; Nukenine et al., 2010; Rice et al., 2011; Kavallieratos et al., 2020; Mantzoukas et al., 2022). Besides, these are pesticidal plant species that have shown potential against mosquitoes (Culicidae) among other blood-feeding insects, as well as arachnid pests (Omolo et al., 2004; Omolo et al., 2022). These plants, traditionally used in pest control, such as those from the families *Asteraceae*, *Lamiaceae*, *Solanaceae*, and *Verbenaceae*, have demonstrated significant insecticidal properties. These plants are often rich in essential oils containing diverse bioactive compounds with pesticidal potential (Omolo et al., 2004; Ngari et al., 2019; Omolo et al., 2022). Essential oils and powdered vegetative material from such plants contain various insecticidal and repellent chemical compounds that could be formulated into biopesticides.

The present study investigated the feeding deterrence and contact toxicity of essential oils from *Lippia javanica*, *Ocimum lamiifolium*, *Ocimum suave*, *Plectranthus marrubioides*, and *Tetradenia riparia* against *Prostephanus. truncatus*. The results of the findings form a basis for the development of biopesticides for insect pests of stored food products and *P. truncatus* in particular.

Fig. 1. Adult *Prostephanus truncatus* (A) (Gueye et al., 2008)

2. Materials and Methods

2.1. Plant material

Fresh aerial plant parts that included leaves, stems, and flowers of *L. javanica*, *O. suave*, *O. lamiifollium*, *P. marrubioides*, and *T. riparia* were collected early in the morning from mature, healthy plants using sterilized secateurs and clean gloves within Baringo and Nakuru counties in Rift Valley, Kenya. Stems of 10–15 cm in length were selectively harvested to ensure uniformity across species. The plant materials were kept under shade, and their oils were extracted within 24 hours of their collection.

2.2. Experimental insects

Experimental insects were derived from a colony of *P. truncatus* maintained at the Centre for African Medicinal and Nutritional Flora and Fauna (CAMNFF) at Masinde Muliro University of Science and Technology (MMUST). The insects were reared on maize seeds (Variety DK 8031, Kenya Seed Company Ltd, Kitale) in 1-liter glass jars with meshed covers and placed in darkness under prevailing laboratory conditions (25 ± 1°C; RH 70-75%).

2.3. Essential oil extraction

A total of 500 g of aerial parts from *Lippia javanica*, *Ocimum suave*, *Ocimum lamiifolium*, *Plectranthus marrubioides*, and *Tetradenia riparia* were subjected to hydro-distillation for 6 hours using a Dean-Stark apparatus to minimize loss of thermolabile volatile compounds, following the method of Eisenbraun & Payne (1999). Plant material was immersed in water and heated to boiling, allowing volatile compounds (essential oils) to evaporate with the steam. The vapor was then condensed, and the immiscible oil layer separated from the water. The extracted essential oils were dried over anhydrous sodium sulfate (Na_2SO_4) to remove residual moisture. The essential oils were collected in 5 mL amber-colored glass vials to protect them from light degradation and stored at 4 °C for subsequent bioassays.

Fig. 2: Damaged maize grain from *P. truncatus* feeding (B) (Kumar, 2002).

2.4. Fumigant and contact toxicity of plant leaves on *Prostephanus truncatus*

Dried maize grains (100 g) mixed with the test plant leaves (20 g) were placed in a transparent plastic jar (500 mL) with four sets of 20 pin holes on four upper sides for aeration. Unsexed adult *P. truncatus* (n=10) were introduced into the jar in four replicates per treatment, including a control comprising maize grains without the leaves. After every 28 days, dead and surviving *P. truncatus* were counted for a period of 6 months.

2.5. Feeding deterrence assay

Feeding deterrence activity was assessed in terms of reduced consumption of maize grains in the form of damage and the number of holes. Dried maize seeds (n=30) were treated for 10 seconds with the oils dissolved in hexane at concentrations (wt/wt) of 10, 5, 2.5, 1.25, and 0.625 %, while the positive control maize received hexane alone, and the negative control was left without any treatment. Both treated and control maize grains were air dried at room temperature for 30 min to allow the solvent to evaporate and then placed in transparent plastic jars (500 mL). Adult *P. truncatus* (n=5) were introduced into each jar before the maize grains were added, and the tests were done in four replicates arranged in a randomized block design (RBD) on a bench. Tests were conducted in four replicates across the treatment concentrations. Each replicate consisted of a separate test jar, and unsexed adult insects were used once per replicate without reusing between treatments. The insects were reared in a dark room under laboratory conditions (25 ± 1°C; RH 70-75%). After 28 days, dead and live *P. truncatus* were counted. The total number of destroyed seeds and holes per seed was used to estimate consumption and hence damage to the maize.

2.6. Analysis of the oil constituents

Analyses of the oils and identification of the chemical components were carried out using an Agilent Gas Chromatograph (GC) (Model 7890B, Country of origin?) coupled to a Quadropolar Mass Spectrometer (QMS) (Model 5977A, Agilent Technologies, US) and GC co-injection of the essential oils with authentic samples (Nangari et al., 2019). Analyses were performed on a capillary Gas Chromatograph (Hewlett Packard (HP) 5890 Series II, equipped with a split-less capillary injector system, 50m·0.2mm (I.d.) crossed-linked methyl silicone (0.33 µm film thickness) capillary column, and flame ionization detector (FID) coupled to HP 3393A Series II integrator. The carrier gas was N_2 at 0.7 mL min^{-1}. The temperature program consisted of an initial 50°C (5 min) to 280°C at 5°C min^{-1} and held at this temperature for 10 min.

Gas Chromatography-Mass Spectrometry (GC-MS) analyses were carried out on an HP 8060 Series II Gas Chromatograph coupled to a VG Platform II Mass Spectrometer. The MS was operated in the EI mode at 70 eV and an emission current of 200 µA. The temperature of the source was held at 180°C and the multiplier voltage at 300 V. The pressure of the ion source and MS detector were held at 9.4×10^{-6} and 1.4×10^{-5}mbar, respectively. The MS had a scan cycle of 1.5s (scan duration of 1s and inter-scan delay of 0.5s). The mass and scan ranges were set at m/z 1–1400 and 38–650, respectively. The instrument was calibrated using hepta-cosafluorotributyl amine, $[CF_3\text{-}(CF2)_3]_3N$, (Apollo Scientific Ltd, UK). The column used for GC-MS was the same as the one described for GC analysis, except for the film thickness (0.5µm). The temperature programme involved an initial temperature of 50°C (5 min), to 90°C at 5°C min^{-1}, to 200°C at 2°C min^{-1}, to 280°C at 20°C $min^{-1,}$ and a hold at this temperature for 20 min. Identification of the components was made by comparison of mass spectra with published data (NIST, Wiley) and confirmed, where possible, by GC co-injections with authentic samples.

2.7. Statistical analysis

Data on *P. truncatus* mortality in the fumigant and contact toxicity assay, as well as data on grain damage and number of holes in the feeding deterrence assay, were subjected to Shapiro wilk test for normality test before subjecting to analysis of variance (ANOVA) in Proc GLM and the means separated using Student-Newman-

Keuls (SNK) t-test in Statistical Analysis System (SAS versions 9.1) (SAS, 2004). Data on *P. truncatus* mortality at different concentrations of essential oils in the feeding deterrence assay were log-transformed and subjected to Probit regression analysis to determine lethal concentrations (LC_{75} and LC_{95}) using EPA Probit Analysis Program version 1.4 (US EPA, 1988

3. Results and Discussion

Mortality of *P. truncatus* was significantly higher in maize grains with leaf material from all five tested plant species compared to the controls by the end of the first month (Table 1), which confirms the pesticidal potential of *L. javanica*, *O. lamiifolia*, *O. suave*, *P. marrubioides*, and *T. riparia* leaves (Bekele et al., 1996; Omolo et al., 2004; Zoubiri & Baaliouamer,2014; Kamanula et al., 2017; Ejeta et al., 2021). By the end of the fifth month, mortality of *P. truncatus* was highest in maize grains that were treated with *P. marrubioides* and *T. riparia* leaves, compared to those treated with *L. javanica*, *O. lamiifolium*, and *O. suave* (Table 1).

Table 1: Mortalities ($Mean \pm SE$) of *Prostephanus truncatus* treated with essential oils from different plant species over a five-month period.

Treatment	Mortalities				
	Month 1	Month 2	Month 3	Month 4	Month 5
Control	0.50 ± 0.28 b	0.50 ± 0.28 c	0.50 ± 0.29 c	0.75 ± 0.25 c	0.75 ± 0.25 c
Lipia javanica	1.75 ± 0.25 a	2.00 ± 0.08 b	2.00 ± 0.08 b	2.75 ± 0.25 b	3.00 ± 0.41 b
Ocimum lamiifollia	1.50 ± 0.64 a	1.50 ± 0.65 b	2.00 ± 0.41 b	2.75 ± 0.25 b	2.50 ± 0.29 b
Ocimum suave	1.25 ± 0.75 a	2.25 ± 0.63 b	2.50 ± 0.50 b	2.78 ± 0.48 b	2.75 ± 0.48 b
Plectranthus marrubioides	2.25 ± 0.25 a	3.50 ± 0.65 a	3.73 ± 0.48 a	3.75 ± 0.48 a	4.50 ± 0.64 a
Tetradenia riparia	1.75 ± 0.48 a	2.00 ± 0.41 b	3.00 ± 0.41 a	3.25 ± 0.25 a	3.75 ± 0.48 a

Means followed by the same letter within a column are not significantly different at P < 0.05 according to the student-Newman-Keuls (SNK) test.

Grain damage and the number of holes in the grains were lower in those treated with essential oils from all five plant species, especially after the first month to the sixth month (Table 2). Grain damage and the number of holes in the grains were lowest in maize grains that were treated with essential oils from *P. marrubioides* and *T. riparia*, compared to those treated with essential oils from *L. javanica*, *O. lamiifollium*, and *O. suave* (Table 2). Grain damage and the number of holes in the grains treated with hexane solvent were lower compared to the controls, with even further reduction in the two parameters when dissolved essential oils from any of the five plant species were present (Table 2). Essential oils from the five plant species exhibited varying efficacies, with *P. marrubioides* being the most effective as per the lowest lethal concentrations (LC_{75} = 0.2; LC_{95} = 1.8), followed by *T. riparia* (LC75 = 5.6; LC95 = 7.0), then L. javanica (LC_{75} = 13.9; LC_{95} = 21.0), *O. suave* (LC_{75} = 55.1; LC_{95} = 78.7) with *O. lamiifollium* having the highest lethal concentration and hence the weakest (LC_{75} = 231.3; LC_{95} = 324.7). Of the nineteen (19) and twelve (12) compounds identified in *Plectranthus marrubioides* and in *Tetradenia riparia*, respectively (Fig. 3 & 4: Table 3), six (6) compounds present in both plant species included *o*-Cymene $C_{10}H_{14}$, 1,8-Cineole $C_{10}H_{18}O$, γ-Terpinene $C_{10}H_{16}$, Fenchone $C_{10}H_{16}O$, Borneol $C_{10}H_{18}O$, and (E) β-Caryophyllene $C_{15}H_{24}$. Some of these compounds have been detected in the genera of the two plant species (Abdel-Mogib et al., 2002; Lukhoba et al., 2006; Blythe et al., 2020), and may include those especially in *Plectranthus* spp, whose chemistry has not been well known (Abdel-Mogib et al., 2002; Lukhoba et al., 2006). The compound *o*-cymene exhibits insecticidal activity through strong fumigant and contact toxicity (Feng et al., 2021), which has been demonstrated against *Tribolium castaneum* and *Liposcelis bostrychophila* (Feng et al., 2021).

However, *o*-cymene has also been found to be attractive to honey bees (Fernandes et al., 2019; Dekebo et al., 2022). The compound 1,8-Cineole exhibits fumigant toxicity as observed against *Musca domestica* (Rossi & Palacios, 2015). Fenchone is part of bioactive chemical compounds in essential oils of *Lavandula dentata* (Lamiaceae), which have been found to exhibit insecticidal activities towards *Sitophilus zeamais*, *Tribolium castaneum,* and *Epicauta atomaria* (Wagner et al., 2021). Insecticidal mechanisms of action 1,8-Cineole and Fenchone include inhibition of acetylcholinesterase (AChE) and cytochrome P450 system, blockage of γ-aminobutyric acid (GABA)-gated chloride channels, and agonist of octopamine receptors (Rossi and Palacios, 2015; Şengül Demirak & Canpolat, 2022). The γ-terpinene compound exhibits larvicidal and ovicidal activities against the cotton bollworm (*Helicoverpa armigera*) (Gong & Ren, 2020). Borneol has been found to inflict mortality on red imported fire ant (*Solenopsis Invicta*) through fumigant toxicity (Zhang et al., 2014). (E)-β-caryophyllene and Caryophyllene oxide exhibit insecticidal, antifeedant, and growth inhibition activities (Langenheim, 1994; Huang et al., 2012; Liu et al., 2012), while acting as a nerve poison to pests through anticholinesterase and via sodium channel modulators, among other mechanisms of action (Liu et al., 2012; Paventi et al., 2020; Sengül Demirak & Canpolat, 2022). Information has been scarce on possible insecticidal mechanisms of Sylvesterene, δ-Cadinene, and γ-Muurolene; as well as whether the remaining three compounds, 7-oxabicyclo [4.1.0] heptan-2-one, 3-methyl, Allo aromadendrene epoxide, and 4-hydroxy,1H indole-3-carboxylic acid detected in *P. marrubioides*, have any insecticidal potential. The other compounds and their mode of action are summarized (Table 4).

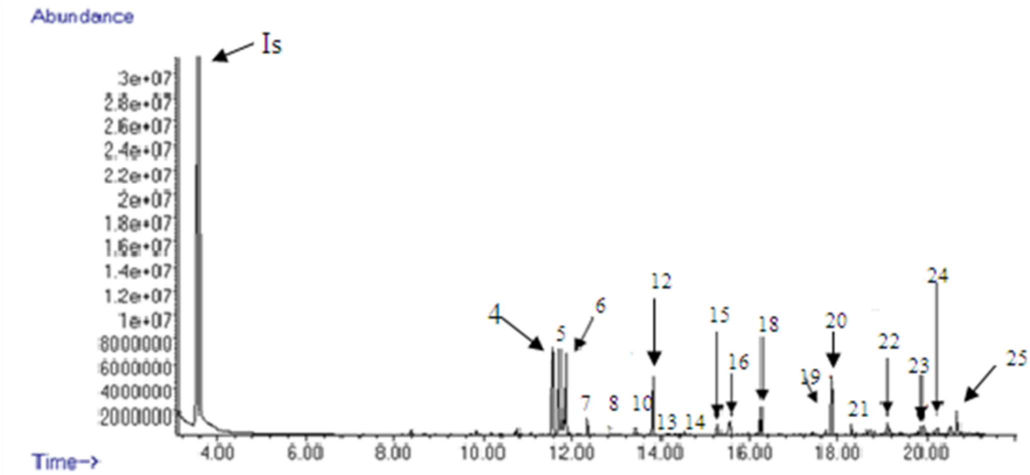

Fig. 3: Total ion chromatogram (TIC) obtained by coupled GC- MS analysis of vacuum distillates of *Plectranthus marrubioides*. Peak numbers correlate to compounds listed in Table 3

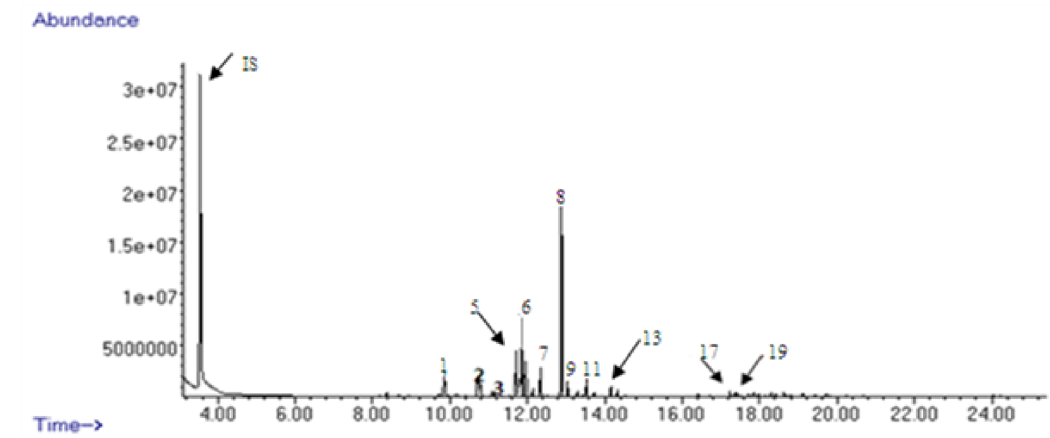

Fig. 4: Total ion chromatogram (TIC) obtained by coupled GC- MS analysis of vacuum distillates of *T. riparia*. Peak numbers correlate to compounds listed in Table 3.

Tetradenia riparia expressed six other chemical compounds that included α-Pinene $C_{10}H_{16}$, β-Pinene $C_{10}H_{16}$, 5-methyl, 3-hepten-2-one $C_8H_{14}O$, E-Ocimene C10H16, Allo Ocimene $C_{10}H_{16}$, and β-Bourbonene $C_{15}H_{24}$. The insecticidal effects of α-Pinene and β-Pinene have been associated with mechanisms of action that include inhibition of AChE and cytochrome P450 system, blockage of GABA-gated chloride channels, and agonist of octopamine receptors (Şengül Demirak & Canpolat, 2022). α-Pinene exhibits a repellent effect to honey bees (Fernandes et al., 2019; Dekebo et al., 2022). β-Bourbonene and (E)-β-ocimene are volatile organic compounds (VOCs) used in indirect plant defenses through attraction of natural enemies towards insect-attacked host plants (Takabayashi et al., 1991; Klimm et al., 2020), while (E)-β-ocimene also attracts pollinators towards floral parts (Knudsen et al., 2004; Tan & Nishida, 2012; Farré-Armengol et al., 2017). E-β-ocimene also partially inhibits ovary development in the worker caste of the honey bees *Apis mellifera* (Maisonnasse et al., 2010). Both β-ocimene and allo-ocimene are volatile pheromones that are the primary signals of *A. mellifera* larvae used in begging for care from the nurses through odorant binding proteins (OBPs)/chemosensory proteins (CSPs) (Maisonnasse et al., 2010; Wu et al., 2019). There is a scarcity of information on possible insecticidal activities of 5-methyl-3-hepten-2-one detected in *T. riparia*.

The general trends in the results of this study indicated that *P. marrubioides* and *T. riparia* inflicted the highest *P. truncatus* mortality, with the least grain damage among the five plant species. Although without statistically significant differences, numerical trends throughout the 6 months indicate that pesticidal compounds of *P. marrubioides* inflicted higher mortalities (Table 1), while those of *T. riparia* had the best effect in reducing grain damage (Table 2). These differences were partly confirmed in the efficacy tests, whereby essential oils of *P. marrubioides* had the lowest lethal concentration and hence the most toxic (LC_{75} = 0.2; LC_{95} = 1.8) compared to *T. riparia* (LC_{75} = 5.6; LC_{95} = 7.0).

The six chemical compounds common in both *P. marrubioides* and *T. riparia* included *o*-Cymene, 1,8-Cineole, γ-Terpinene, Fenchone, Borneol, and (E) β-Caryophyllene, and accounted for 25% and 44.8% total concentration in *P. marrubioides* and *T. riparia*, respectively. Trends in the concentrations of these six

Table 2: Mean ± SE of seed damage and number of holes by *Callosobruchus maculatus* over six months

Treatment	Month 1		Month 2		Month 3		Month 4		Month 5		Month 6	
	Damage	Holes	Damage	Holes	Damage	Holes	Damage	Holes	Damage	Holes	Damage	Holes
Control	4.0 ± 0.4 a	31.3 ± 6.0 a	6.3 ± 0.5 a	60.0 ± 1.8 a	9.0 ± 0.4 a	73.0 ± 1.4 a	10.8 ± 0.5 a	79.3 ± 3.3 a	14.5 ± 1.6 a	86.3 ± 3.4 a	16.3 ± 1.1 a	91.8 ± 4.5 a
Hexane	1.3 ± 0.3 b	3.8 ± 0.9 b	3.0 ± 0.4 b	27.0 ± 4.8 b	3.3 ± 0.3 b	40.0 ± 4.4 b	4.3 ± 0.8 b	46.8 ± 4.6 b	5.5 ± 0.7 b	53.5 ± 5.0 b	7.8 ± 0.8 b	61.3 ± 3.8 b
L. javanica [1]	0.8 ± 0.2 b	0.9 ± 0.2 c	1.4 ± 0.2 d	1.5 ± 0.2 d	1.6 ± 0.1 d	2.6 ± 0.3 c	1.8 ± 0.1 c	3.0 ± 0.3 c	2.1 ± 0.2 c	3.6 ± 0.4 c	2.5 ± 0.2 c	4.1 ± 0.4 c
O. lamiifollia [2]	1.2 ± 0.1 b	1.2 ± 0.1 c	1.8 ± 0.1 c	2.1 ± 0.1 c	1.9 ± 0.1 c	2.3 ± 0.1 c	2.0 ± 0.1 c	2.6 ± 0.1 c	2.3 ± 0.1 c	2.9 ± 0.2 d	2.4 ± 0.1 c	3.1 ± 0.1 d
O. suave [3]	1.4 ± 0.1 b	1.5 ± 0.2 c	1.6 ± 0.2 c	2.1 ± 0.2 c	1.9 ± 0.1 c	2.6 ± 0.2 c	2.0 ± 0.1 c	2.9 ± 0.2 c	2.4 ± 0.1 c	3.2 ± 0.2 c	2.6 ± 0.1 c	3.6 ± 0.2 c
P. marrubioides [4]	0.1 ± 0.1 c	0.1 ± 0.1 d	0.3 ± 0.1 e	0.4 ± 0.1 e	0.5 ± 0.2 e	0.5 ± 0.2 d	0.5 ± 0.2 d	0.6 ± 0.2 d	0.6 ± 0.2 d	0.6 ± 0.2 e	0.6 ± 0.2 d	0.7 ± 0.2 e
T. riparia [5]	0.0 ± 0.0 c	0.0 ± 0.0 e	0.2 ± 0.1 e	0.2 ± 0.1 e	0.3 ± 0.1 e	0.4 ± 0.1 d	0.4 ± 0.1 d	0.5 ± 0.1 d	0.4 ± 0.1 d	0.5 ± 0.1 e	0.4 ± 0.1 d	0.5 ± 0.2 e

Values followed by different letters within the same column are significantly different ($p < 0.05$). Damage refers to the number of seeds visibly damaged by bruchid activity, while holes indicate perforations on seed surfaces. Lethal concentrations (LC_{75}; LC_{90}) for [1] *L. javanica* (13.9; 21.0), [2] *O. lamiifollia* (231.3; 324.7), [3] *O. suave* (55.1; 78.7), [4] *P. marrubioides* (0.2; 1.8), *and* [5] *T. riparia* (5.6; 7.0).

Table 3: The chemical compositions of essential oils of *Plectranthus marrubioides* and *Tetradenia riparia* plants

	Plectranthus marrubioides			*Tetradenia riparia*		
Peak	Retention time	% Area	Peak identity	Retention time	% Area	Peak identity
1	11.58	10.84	δ 2- Carene	9.87	2.92	α-Pinene
2	11.73	8.72	*o*-Cymene*	10.77	5.23	β- Pinene
3	11.84	7.89	1,8- Cineole*	11.17	0.57	5-methyl, 3-hepten-2-one
4	12.34	1.47	γ-Terpinene*	11.73	5.16	*o*-Cymene*
5	12.9	0.81	Fenchone*	11.84	10.89	1,8-Cineole*
6	13.43	0.69	Cyclooctanone	12.34	1.89	γ- Terpinene*
7	13.84	5.65	Camphor	12.9	24.74	Fenchone*
8	14.17	0.32	Borneol, heptafluorobutyrate*	13.05	1.55	E-Ocimene
9	14.33	0.61	Terpinen-4-ol	13.52	1.7	Allo Ocimene
10	15.29	1.02	iso-Sylvesterene	14.17	1.51	Borneol*
11	15.56	2.25	7-oxabicyclo [4.1.0] heptan-2one,3methyl	17.4	1.01	β-Bourbonene
12	17.44	0.47	Germacrene A	17.71	0.63	(E)-Caryophyllene*
13	17.87	5.79	(E)-Caryophyllene*	-	-	-
14	18.29	0.89	α-Humulene	-	-	-
15	19.12	1.26	δ- Cadinene	-	-	-
16	19.82	1.45	Allo aromadendrene epoxide	-	-	-
17	20.27	1.34	4 Hydroxy, 1H indole -3-carboxylic acid	-	-	-
18	20.69	2.88	α-Cadinol	-	-	-
19	21.14	0.54	γ-Muurolene	-	-	-

*Chemical compound exists in both plant species chemical compounds indicate that, apart from o-Cymene, which was in higher concentration in *P. marrubioides*, the other five compounds, and especially Fenchone, were in higher concentrations in *T. riparia*. Furthermore, with a smaller number of compounds detected in *T. riparia*, those twelve (12) compounds accounted for 57.8% of the total concentration, while the nineteen (19) compounds detected in *P. marrubioides* accounted for a lower concentration of 54.9%. The diversity and concentration of chemical compounds in the essential oils of *Plectranthus marrubioides* may suggest the potential for synergistic interactions contributing to the observed insecticidal efficacy. However, such synergism was not directly assessed in the present study and remains a subject for future investigation, when compared to *T. riparia*, whose efficacy may have been more reliant on the high concentration of Fenchone (24.74%). However, this assumption does not exclude the possible involvement of other insecticidal chemical compounds in the two plant species, including alkaloids (Rattray & Van Wyk, 2021), which may not have been detected in the GC-MS analyses applied in the current study. Essential oils of *P. marrubioides* and *T. riparia* show insecticidal and feeding deterrent effects against *P. truncatus*, supporting their potential as biopesticides. However, formulation and delivery remain unknown. Future studies should assess formulation stability, safety, and field applicability.

Table 4: *Plectranthus marrubioides* chemical compounds and their mode of action.

Compound name	Mode of Action / Effect	References
Camphor ($C_{10}H_{16}O$)	Contact & fumigant toxicity to *S.granarius, S.zeamais, T.castaneum, P.truncatus* AChE inhibition	(Obeng-Ofori et al., 1998)
δ 2-Carene ($C_{10}H_{16}$)	Fumigant toxicity to *C. maculatus, S. oryzae, T. castaneum*; AChE inhibition	(Hashemi & Safavi, 2012)
α-Cadinol ($C_{15}H_{26}O$)	AChE inhibition	(Rants'o et al., 2022)
Terpinen-4-ol ($C_{10}H_{18}O$)	Toxic to Oriental armyworm via P450, GSTs, PPO inhibition	(Zhang, 2008)
iso-Sylvesterene ($C_{10}H_{16}$)	Contact toxicity; causes mortality and developmental disruption in *D. peruvianus, An.gambiae, Cx. quinquefasciatus*	(Pacheco et al., 2020)
Germacrene A ($C_{15}H_{24}$)	Indirect defense via attraction of predators; aphid alarm pheromone precursor	(Huber et al., 2016)
Cyclooctanone ($C_8H_{14}O$)	Alarm pheromone in ants (Pogonomyrmex badius)	(Blum, 1969; Blum et al., 1971)
α-Humulene ($C_{15}H_{24}$)	Contact toxicity; inhibits respiratory chain complexes II-IV	(Kim & Lee, 2014; Paventi et al., 2020; Plata-Rueda et al., 2018)
δ-Cadinene ($C_{15}H_{24}$)	Insecticidal activity against Bruchus dentipes, *An. stephensi, Ae. aegypti, Cx. quinquefasciatus*	(Govindarajan & Benelli, 2016; Tozlu et al., 2011; Vaglica et al., 2022)
γ-Muurolene ($C_{15}H_{24}$)	Toxicity to Bruchus dentipes	(Vaglica et al., 2022)

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References

Abdel-Mogib, M., Albar, H.A., Batterjee, S.M., 2002. Chemistry of the Genus Plectranthus. *Molecules* 7(2), 271-301. https://doi.org/10.3390/70200271.

Bekele, A.J, Obeng-ofori, D., Hassanali, A., 1996. Evaluation of Ocimum suave (Willd) as a source of repellents, toxicants and protectants in storage against three stored product insect pests. International *Journal of Pest Management* 42(2), 139-142. https://doi.org/10.1080/09670879609371983.

Bezabih, G., Satheesh, N., Workneh Fanta, S., Wale, M., Atlabachew, M., 2022. Reducing postharvest loss of stored grains using plant-based biopesticides: A review of past research efforts. *Advances in Agriculture* 2022. https://doi.org/10.1155/2022/6946916.

Blum, M.S., 1969. Alarm pheromones. *Annual Review of Entomology* 14, 57-80. https://doi.org/10.1146/annurev.en.14.010169.000421.

Blum, M.S., Doolittle, R.E., Beroza, M., 1971. Alarm pheromones: Utilization in evaluation of olfactory theories. *Journal of Insect Physiology* 17, 2351-2361. https://doi.org/10.1016/0022-1910(71)90083-7.

Blythe, E.K., Tabanca, N., Demirci, B., Kendra, P.E., 2020. Chemical composition of essential oil from Tetradenia riparia and its attractant activity for Mediterranean Fruit Fly, Ceratitis capitata. *Natural Product Communications* 15(9). https://doi.org/10.1177/1934578X20953955

Danso, J.K., Osekre, E.A., Opit, G.P., Manu, N., Armstrong, P., Arthur, F.H., Campbell, J.F., Mbata, G., McNeill, S.G., 2018. Post-harvest insect infestation and mycotoxin levels in maize markets in the Middle Belt of Ghana. *Journal of Stored Products Research* 77, 9-15. https://doi.org/10.1016/j.jspr.2018.02.004

Dekebo, A., Kim, M.J., Son, M., Jung, C., 2022. Comparative analysis of volatile organic compounds from flowers attractive to honey bees and bumblebees. *Journal of Ecology and Environment* 46(1), 62-75. https://doi.org/10.5141/jee.21.001

Diagne, C., Leroy, B., Vaissière, A.-C., Gozlan, R. E., Roiz, D., Jarić, I., Salles, J.-M., Bradshaw, C. J. A., … Courchamp, F. (2021). High and rising economic costs of biological invasions worldwide. *Nature*, 592(7855), 571–576. https://doi.org/10.1038/s41586-021-03405-6

Dunstan, W.R., Magazini, I.A., 1981. Outbreaks and new records, United Republic of Tanzania. The larger grain borer on stored products. *FAO Plant Protection Bulletin* 29(3/4), 80–1.

Eisenbraun, E.J., Payne, K.W., 1999. Dean-Stark Apparatus Modified for Use with Molecular Sieves. Industrial and Engineering Chemistry Research 38(12), 4521-4524. https://doi.org/10.1021/ie9904044

Ejeta, D., Asme, A., Asefa, A., 2021. Insecticidal effect of ethnobotanical plant extracts against Anopheles arabiensis under laboratory conditions. *Malaria Journal* 20, 466. https://doi.org/10.1186/s12936-021-04004-6.

Farré-Armengol, G., Filella, I., Llusià, J., Peñuelas, J. 2017. β-Ocimene, a key floral and foliar volatile involved in multiple interactions between plants and other organisms. *Molecules* 22(7), 1148. https://doi.org/10.3390/molecules22071148.

Farrell, G., Schulten, G., 2002. Larger Grain Borer in Africa; A history of efforts to limit its impact. Integrated Pest Management *Reviews* 7, 67–84. https://doi.org/10.1023/A:1026345131876.

Feng, Y.X., Zhang, X., Wang, Y., Chen, Z.Y., Lu, X.X., Du, Y.S., Du, S.S., 2021. The potential contribution of cymene isomers to insecticidal and repellent activities of the essential oil from Alpinia zerumbet. *International Biodeterioration and Biodegradation* 157, p.105138. https://doi.org/10.1016/j.ibiod.2020.105138.

Fernandes, N., Silva, F.A.N., de Aragão, F., Zocolo, G.J., Freitas, B.M., 2019. Volatile organic compounds role in selective pollinator visits to commercial melon types. *Journal of Agricultural Science* 11(3), 93-108. https://doi.org/10.5539/jas.v11n3p93.

Gariba, S.Y., Dzidzienyo, D.K., Eziah, V.Y., 2021. Assessment of four plant extracts as maize seed protectants against Sitophilus zeamais and Prostephanus truncatus in Ghana. *Cogent Food and Agriculture* 7(1), p.1918426. https://doi.org/10.1080/23311932.2021.1918426.

Gong, X., Ren, Y., 2020. Larvicidal and ovicidal activity of carvacrol, p-cymene, and γ-terpinene from Origanum vulgare essential oil against the cotton bollworm, Helicoverpa armigera (Hübner). *Environmental Science and Pollution Research* 27, 18708–18716. https://doi.org/10.1007/s11356-020-08391-2.

Govindarajan, M., Benelli, G., 2016. α-Humulene and β-elemene from Syzygium zeylanicum (Myrtaceae) essential oil: highly effective and eco-friendly larvicides against Anopheles subpictus, Aedes albopictus, and Culex tritaeniorhynchus (Diptera: Culicidae). Parasitology Research 115, 2771–2778. https://doi.org/10.1007/s00436-016-5025-2.

Gueye, M.T., Goergen, G., Badiane, D., Hell, K., Lamboni, L., 2008. First report on occurrence of the larger grain borer Prostephanus truncatus (Horn)(Coleoptera: Bostrichidae) in Senegal. African Entomology 16(2), 309-311. https://doi.org/10.4001/1021-3589-16.2.309.

Han, X.L., Feng, J.T., Li, G.Z., Zhang, X., 2008. Effects of terpinen-4-ol on four metabolic enzymes and polyphenol oxidase (PPO) in Mythimna separta Walker. *Agricultural Sciences in China* 7(6), 726-730. https://doi.org/10.1016/S1671-2927(08)60107-8.

Hashemi, S.M., Safavi, S.A., 2012. Chemical constituents and toxicity of essential oils of oriental arborvitae, Platycladus orientalis (L.) Franco, against three stored-product beetles. *Chilean Journal of Agricultural Research* 72(2), 188. http://dx.doi.org/10.4067/S0718-58392012000200004.

Huang, M., Sanchez-Moreiras, A.M., Abel, C., Sohrabi, R., Lee, S., Gershenzon, J., Tholl, D., 2012. The major volatile organic compound emitted from Arabidopsis thaliana flowers, the sesquiterpene (E)-β-caryophyllene, is a defense against a bacterial pathogen. *New Phytologist* 193(4), 997-1008. https://doi.org/10.1111/j.1469-8137.2011.04001.x .

Huber, M., Epping, J., Gronover, C.S., Fricke, J., Aziz, Z., Brillatz, T. et al., 2016. A latex metabolite benefits plant fitness under root herbivore attack. *PLoS Biology* 14(1), e1002332. https://doi.org/10.1371/journal.pbio.1002332.

Kamanula, J.F., Belmain, S.R., Hall, D.R., Farman, D.I., Goyder, D.J., Mvumi, B.M., Masumbu, F.F., Stevenson, P.C., 2017. Chemical variation and insecticidal activity of Lippia javanica (Burm. f.) Spreng essential oil against Sitophilus zeamais Motschulsky. *Industrial Crops and Products* 110, 75-82. https://doi.org/10.1016/j.indcrop.2017.06.036

Kavallieratos, N.G., Boukouvala, M.C., Ntalli, N., Skourti, A., Karagianni, E.S., Nika, E.P., Kontodimas, D.C., Cappellacci, L., Petrelli, R., Cianfaglione, K., Morshedloo, M.R., 2020. Effectiveness of eight essential oils against two key stored-product beetles, Prostephanus truncatus (Horn) and Trogoderma granarium Everts. *Food and Chemical Toxicology* 139, p.111255. https://doi.org/10.1016/j.fct.2020.111255

Kheseli, P.O., Ochanda, J.O., Okoth, S.A., 2011. Evaluation of potency of native Bacillus thuringiensis against maize insect pests and aflatoxin producing fungi in Kenya. *Journal of Tropical Microbiology and Biotechnology* 7(1), 9-15. https://www.ajol.info/index.php/jtmb/article/view/75427.

Kim, S.I., Lee, D.W., 2014. Toxicity of basil and orange essential oils and their components against two coleopteran stored products insect pests. Journal of Asia-Pacific Entomology, 17(1), 13-17. https://doi.org/10.1016/j.aspen.2013.09.002.

Klimm, F.S., Weinhold, A., Volf, M., 2020. Volatile production differs between oak leaves infested by leaf-miner Phyllonorycter harrisella (Lepidoptera: Gracillariidae) and galler Neuroterus quercusbaccarum (Hymenoptera: Cynipidae). *European Journal of Entomology* 117, 101–109. https://doi.org/10.14411/eje.2020.011.

Knudsen, J.T., Tollsten, L., Groth, I., Bergström, G., Raguso, R.A., 2004. Trends in floral scent chemistry in pollination syndromes: floral scent composition in hummingbird-pollinated taxa. *Botanical Journal of the Linnean Society* 146(2), 191–199. https://doi.org/10.1111/j.1095-8339.2004.00329.x

Kumar, H., 2002. Resistance in maize to the larger grain borer, Prostephanus truncatus (Horn)(Coleoptera: Bostrichidae). *Journal of Stored Products Research*, 38(3), 267-280. https://doi.org/10.1016/S0022-474X(01)00030-3.

Lamboni, Y., Hell, K., 2009. Propagation of mycotoxigenic fungi in maize stores by post-harvest insects. International *Journal of Tropical Insect Science* 29, 31–39. https://doi.org/10.1017/S1742758409391511.

Langenheim, J.H., 1994. Higher plant terpenoids: A phytocentric overview of their ecological roles. *Journal of Chemical Ecology* 20, 1223–1280. https://doi.org/10.1007/BF02059809.

Liu, P., Liu, X-C., Dong, H-W., Liu, Z-L., Du, S-S., Deng, Z-W., 2012. Chemical composition and insecticidal activity of the essential oil of Illicium pachyphyllum fruits against two grain storage insects. *Molecules* 17(12), 14870-14881. https://doi.org/10.3390/molecules171214870.

Lukhoba, C.W., Simmonds, M.S.J., Paton, A.J., 2006. Plectranthus: a review of ethnobotanical uses. *Journal of Ethnopharmacology* 103(1), 1-24. https://doi.org/10.1016/j.jep.2005.09.011.

Maisonnasse, A., Lenoir, J.C., Beslay, D., Crauser, D., Le Conte, Y., 2010. E-β-ocimene, a volatile brood pheromone involved in social regulation in the honey bee colony (Apis mellifera). *PLoS One* 5(10), e13531. https://doi.org/10.1371/journal.pone.0013531.

Mantzoukas, S., Kalyvas, N., Ntoukas, A., Lagogiannis, I., Farsalinos, K., Eliopoulos, P.A., Poulas, K., 2020. Combined toxicity of cannabidiol oil with three bio-pesticides against adults of Sitophilus zeamais, Rhyzopertha dominica, Prostephanus truncatus and Trogoderma granarium. *International Journal of Environmental Research and Public Health* 17(18), p.6664. https://doi.org/10.3390/ijerph17186664.

Mantzoukas, S., Korbou, G., Lagogiannis, I. et al., 2022. Effect of hellebore (Helleborus odorus Waldst. & Kit. ex Willd.) plant extract on the progeny and survival of the larvae of stored product pests. *Journal of Plant Diseases and Protection* 129, 349-356. https://doi.org/10.1007/s41348-022-00568-w.

Nang'ayo, F.L.O., Hill, M.G., Wright, D.J., 2002. Potential hosts of Prostephanus truncatus (Coleoptera: Bostrichidae) among native and agroforestry trees in Kenya. *Bulletin of Entomological Research* 92, 499-506. https://doi.org/10.1079/ber2002202.

Ngari A.G., Omolo, M.V., Tarus P.K., Ng'ang'a M.M., Hassanali, A., 2019. Chemical compositions of fresh volatiles aromas of some Kenyan Ocimum species. *Journal of Pharmacognosy and Phytochemistry* 8(6), 201-208. https://www.phytojournal.com/archives/2019/vol8issue6/PartC/8-4-693-995.pdf.

Nukenine, E.N., Adler, C., Reichmuth, C., 2010. Efficacy of Clausena anisata and Plectranthus glandulosus leaf powder against Prostephanus truncatus (Coleoptera: Bostrichidae) and two strains of Sitophilus zeamais (Coleoptera: Curculionidae) on maize. *Journal of Pest Science* 83, 181–190. https://doi.org/10.1007/s10340-009-0285-6.

Obeng-Ofori, D., Reichmuth, C.H., Bekele, A.J., Hassanali, A., 1998. Toxicity and protectant potential of camphor, a major component of essential oil of Ocimum kilimandscharicum, against four stored product beetles. *International Journal of Pest Management* 44(4), 203-209. https://doi.org/10.1080/096708798228112.

Okwute, S.K., 2012. Plants as potential sources of pesticidal agents: a review. *Pesticides-Advances in Chemical and Botanical Pesticides* 10, 208-232. https://doi.org/10.5772/46225.

Omolo, M.O., Okinyo, D., Ndiege, I.O., Lwande, W., Hassanali, A., 2004. Repellency of essential oils of some Kenyan plants against Anopheles gambiae. *Phytochemistry* 65(20), 2797-2802. https://doi.org/10.1016/j.phytochem.2004.08.035.

Omolo, M.V., Wafula, V.M., Andati, R.E., Owino, J.O., 2022. Bio-pesticide composition for killing jiggers and other blood feeding insects and arachnid pests. *World Intellectual Property Organization (WIPO)* Patent Ref: WO2011038120A1 2011-03-3.

Pacheco, J.P.F., Nogueira, J., de Miranda, R.P.R., Duprat, R.C., Machado, F.P., Tietbohl, L.A.C., Mourão, S.C., Santos, M.G., Ratcliffe, N.A., Penna, P.A., de Mello Neto, C.B., 2020. Effects of Zanthoxylum caribaeum essential oil against cotton bug Dysdercus peruvianus. *Research, Society and Development* 9(9), 9. https://doi.org/10.33448/rsd-v9i9.7152.

Paventi, G., de Acutis, L., De Cristofaro, A., Pistillo, M., Germinara, G.S., Rotundo, G., 2020. Biological activity of Humulus lupulus (L.) essential oil and its main components against Sitophilus granarius (L.). *Biomolecules* 10(8), 1108. https://doi.org/10.3390/biom10081108.

Plata-Rueda, A., Campos, J.M., da Silva Rolim, G., Martínez, L.C., Dos Santos, M.H., Fernandes, F.L., Serrão, J.E., Zanuncio, J.C., 2018. Terpenoid constituents of cinnamon and clove essential oils cause toxic effects and behavior repellency response on granary weevil, Sitophilus granarius. *Ecotoxicology and Environmental Safety* 156, 263-270. https://doi.org/10.1016/j.ecoenv.2018.03.033.

Ponsankar, A., Vasantha-Srinivasan, P., Senthil-Nathan, S., Thanigaivel, A., Edwin, E.S., Selin-Rani, S., Kalaivani, K., Hunter, W.B., Alessandro, R.T., Abdel-Megeed, A., Paik, C.H., 2016. Target and non-target toxicity of botanical insecticide derived from Couroupita guianensis L. flower against generalist herbivore, Spodoptera litura Fab. and an earthworm, Eisenia foetida Savigny. *Ecotoxicology and Environmental Safety* 133, 260-270. https://doi.org/10.1016/j.ecoenv.2016.06.043.

Quellhorst, H., Athanassiou, C.G., Zhu, K.Y., Morrison III, W.R., 2021. The biology, ecology and management of the larger grain borer, Prostephanus truncatus

(Horn) (Coleoptera: Bostrichidae). *Journal of Stored Products Research* 94, p.101860. https://doi.org/10.1016/j.jspr.2021.101860.

Quellhorst, H.E., Arthur, F.H., Bruce, A., Zhu, K.Y., Morrison III, W.R., 2022. Exposure to a novel insecticide formulation on maize and concrete reduces movement by the stored product pests, Prostephanus truncatus (Horn) and Sitophilus zeamais (Motschulsky). *Frontiers in Agronomy* 4, 868509. https://doi.org/10.3389/fagro.2022.868509.

Rants'o, T.A., Koekemoer, L.L., Panayides, J-L., van Zyl, RL., 2022. Potential of Essential Oil-Based Anticholinesterase Insecticides against Anopheles Vectors: A Review. Molecules 27(20), 7026. https://doi.org/10.3390/molecules27207026.

Rattray, R.D., Van Wyk, B-E., 2021. The botanical, chemical and ethnobotanical diversity of Southern African Lamiaceae. *Molecules* 26(12), 3712. https://doi.org/10.3390/molecules26123712.

Rice, L.J., Brits, G.J., Potgieter, C.J., Van Staden, J., 2011. Plectranthus: A plant for the future? *South African Journal of Botany* 77(4), 947-959. https://doi.org/10.1016/j.sajb.2011.07.001.

Riyaz, M., Mathew, P., Zuber, S.M., Rather, G.A., 2022. Botanical pesticides for an eco-friendly and sustainable agriculture: New challenges and prospects. In: Bandh, S.A. (ed) Sustainable Agriculture. *Springer*, Cham. https://doi.org/10.1007/978-3-030-83066-3_5.

Rossi, Y.E., Palacios, S.M., 2015. Insecticidal toxicity of Eucalyptus cinerea essential oil and 1, 8-cineole against Musca domestica and possible uses according to the metabolic response of flies. *Industrial Crops and Products* 63, 133-137. https://doi.org/10.1016/j.indcrop.2014.10.019.

SAS, 2004. SAS/STAT ® 9.1 User's Guide. Cary, NC: SAS Institute Inc. https://support.sas.com/documentation/onlinedoc/91pdf/sasdoc_91/stat_ug_7313.pdf.

Şengül Demirak, MŞ., Canpolat, E., 2022. Plant-based bioinsecticides for mosquito control: Impact on insecticide resistance and disease transmission. *Insects* 13(2), 162. https://doi.org/10.3390/insects13020162.

Takabayashi, J., Dicke, M., Posthumus, M.A., 1991. Induction of indirect defence aganist spider-mites in uninfested lima bean leaves. *Phytochemistry* 30(5), 1459-1462. https://doi.org/10.1016/0031-9422(91)84186-V.

Tan, K.H., Nishida, R., 2012. Methyl Eugenol: its occurrence, distribution, and role in nature, especially in relation to insect behavior and pollination. Journal of Insect Science 12(56), 1-60. https://doi.org/10.1673/031.012.5601.

Tanda, A.S., Kumar, M., Tamta, A.K., Deeksha, M.G., 2022. Advances in integrated management technology of insect pests of stored grain. In: Tanda, A.S. (ed) Advances in Integrated Pest Management Technology. *Springer*, Cham. https://doi.org/10.1007/978-3-030-94949-5_8.

Tozlu, E., Cakir, A., Kordali, S., Tozlu, G., Ozer, H., Akcin, T.A., 2011. Chemical compositions and insecticidal effects of essential oils isolated from Achillea gypsicola, Satureja hortensis, Origanum acutidens and Hypericum scabrum against broadbean weevil (Bruchus dentipes). *Scientia Horticulturae* 130(1), 9-17. https://doi.org/10.1016/j.scienta.2011.06.019.

US EPA, 1988. EPA Probit Analysis Program used for calculating EC values. Version 1.4. Biological Methods Branch, Environmental Monitoring and Support Laboratory, United States Environmental Protection Agency (US EPA), Cincinnati, Ohio, US.

Vaglica, A., Peri, E., Badalamenti, N., Ilardi, V., Bruno, M., Guarino, S., 2022. Chemical composition and evaluation of insecticidal activity of Seseli bocconei essential oils against stored products pests. Plants 11, 3047. https://doi.org/10.3390/plants11223047.

Vowotor, K.A., Meikle, W.G., Ayertey, J.N. et al., 1998. Intraspecific competition in larvae of the Larger Grain Borer, Prostephanus truncatus (Horn) within maize grains. *International Journal of Tropical Insect Science* 18, 171–175. https://doi.org/10.1017/S1742758400023365.

Wagner, L.S., Sequin, C.J., Foti, N., Campos-Soldini, M.P., 2021. Insecticidal, fungicidal, phytotoxic activity and chemical composition of Lavandula dentata essential oil. *Biocatalysis and Agricultural Biotechnology* 35, p.102092. https://doi.org/10.1016/j.bcab.2021.102092.

Wu, F., Feng, Y., Han, B., Hu, H., Feng, M., Meng, L., Ma, C., Yu, L., Li, J., 2019. Mechanistic insight into binding interaction between chemosensory protein 4 and volatile larval pheromones in honeybees (Apis mellifera). *International Journal of Biological Macromolecules* 141, 553-563. https://doi.org/doi: 10.1016/j.ijbiomac.2019.09.04.

Zhang, N., Tang, L., Hu, W., Wang, K., Zhou, Y., Li, H., Huang, C., Chun, J., Zhang, Z., 2014. Insecticidal, fumigant, and repellent activities of sweet wormwood oil and its individual components against red imported fire ant workers (Hymenoptera: Formicidae). *Journal of Insect Science* 14(1). https://doi.org/10.1093/jisesa/ieu103.

Zhang Y., Wang L., Wu K., Wyckhuys K. A. G., Heimpel G. E. (2008). Flight performance of the soybean aphid, Aphis glycines (Hemiptera: Aphididae), under different temperature and humidity regimens. *Environmental Entomology*, 37, 301-306.

Zoubiri, S., Baaliouamer, A., 2014. Potentiality of plants as source of insecticide principles. *Journal of Saudi Chemical Society* 18(6), 925-938. https://doi.org/10.1016/j.jscs.2011.11.015.

Martínez-Guerra, G., Ramírez-Ramírez, I., Maldonado-Peralta, R., Marshall, L., Bosch, C., Cruz-Huerta, N., & Gonzalez-Santos, R. (2021). The importance of conserving Mexico's tomato agrodiversity to research plant biochemistry under different climates. *Plants, People, Planet*, 3(6), 703–709.

Tansakul, N., & Yenradee, P. (2020). Fuzzy improvement-project portfolio selection considering financial performance and customer satisfaction. *International Journal of Knowledge and Systems Science* (IJKSS), 11(2), 41–70.

Tarbet, J. E., Oura, M., & Sternberg, T. H. (1953). Microassay of antifungal properties of steroid hormones and other compounds. *Mycologia*, 45(5), 627–648.

Zhu, C., Lei, M., Andargie, M., Zeng, J., & Li, J. (2019). Antifungal activity and mechanism of action of tannic acid against Penicillium digitatum. *Physiological and Molecular Plant Pathology*, 107, 46–50.