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Evaluation of the efficacy of steam-extracted garlic oil on cowpea beetle [*Callosobruchus maculatus* (F.)] Coleoptera under semi-storage conditions

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ABSTRACT

The cowpea beetle, *Callosobruchus maculatus* (F.), is a major insect pest of stored products, causing significant damage and economic losses. A study was carried out to evaluate the fumigant efficacy of the steam extract of Sudanese garlic (*Allium sativum* L.) oil against *C. maculatus* (F.) under semi-storage conditions. The garlic oils were tested at concentrations of 0.001, 0.005, 0.01, 0.05, 0.1, and 1% at a one-week exposure period using fumigant bioassays. Phosphine (PH_3) was used as a standard, and control treatment sets were included. Results indicated that the garlic oils were effective and caused significantly ($P \leq 0.05$) superior mortality (insect recoveries were observed for 4 days) among the tested insects compared to the control and the standard phosphine. Statistical analysis revealed that *C. maculatus* (F.) was highly sensitive to garlic oil vapors and resulted in 100% mortality within one week. The results indicate that the respective Lethal–concentrations (mg/l), LC_{10}, LC_{50}, and LC_{90} in the plastic cups were: 4.35×10^{-4}, 6.53×10-4, and 1.01×10-4 mg/l, while in the jute sac, they were: 3.06×10^{-4}, 6.95×10^{-4}, and 1.38×10^{-4} mg/l, (after a week of exposure), respectively. Overall, the fumigant activity of *A. sativum* (L.) EO may offer an environmentally friendly strategy to manage stored-product pests under laboratory and storage conditions.

Keywords: garlic oil, fumigant activity, *Callosobruchus maculatus* (F.), semi-storage

INTRODUCTION

Cowpea (*Vigna unguiculata* (L.) Walpers) is an ancient food crop domesticated in Africa, likely before 2500 BCE (Herniter et al., 2020), and has probably been used as a crop plant since Neolithic times (Gonçalves et al., 2016). It spread globally, reaching major production regions in the Old World by 400 BCE and later to the Americas during the Columbian exchange (Singh, 2015). Cowpea is a significant source of dietary protein in developing nations, with over 12 million acres produced annually. The crop is valued for its nutritional content, including proteins, carbohydrates, vitamins, and minerals. The cowpea also has medicinal uses and can fix up to 80% of the soil nitrogen (Abebe and Alemayehu, 2022). In the United States, cowpeas were historically grown for soil management and livestock feed, and the country ranked among the top 10 global producers until 1967. With changing demographics, cowpea consumption in the U.S.A. is expected to increase substantially (Adewale et al., 2021).

Many countries depend on cowpea as a source of energy and as a rich source of protein (Pandey et al., 2016). A lack of archaeological evidence has led to conflicting

views on the origins of Africa, Asia, and South America. Some literature indicates that cowpea was introduced from Africa to the Indian subcontinent approximately 2000 to 3500 years ago, at the same time as the introduction of sorghum and millet, while others state that before the year 300 BC (Boukar et al., 2019). Cowpeas had reached Europe and possibly North Africa from Asia. It is thought that the cultivated cowpea is native to India, Africa, or South America (Herniter et al., 2020). However, cowpea is now grown throughout the tropics and subtropics and is part of the diet of about 110 million people (Gonçalves et al., 2016; Boukar et al., 2019; Maqbool et al., 2021). Some believe cowpea originated from West Africa because both wild and cultivated species are found in this region (Gonçalves et al., 2016; Boukar et al., 2019; Maqbool et al., 2021). Others believe that it originates from Southern Africa. Its production has spread to East and Central Africa, India, Asia, South and Central America (Gonçalves et al., 2016; Boukar et al., 2019; Maqbool et al., 2021). Cowpea is reported to be attacked by various insect pests during both the pre-harvest and storage stages. Among the post-harvest pests, *Callosobruchus maculatus* (F.) is recognized as one of the major insect pests (Mahfuz and Khalequzzaman, 1970). This insect causes severe damage to cowpea seeds by reducing seed quality and market value (Mahgoub et al., 2017). In Sudan and other parts of Africa, the post-harvest losses of cowpea seeds range from 5-10% due to *C. maculatus* (F.) infestation (Kumar and Kalita, 2017).

These problems have stimulated interest in identifying safe alternatives for the control of *Callosobruchus maculatus* (F.), particularly botanical products. Plant secondary metabolites represent one of the most important sources of natural compounds (Srivastava and Kumar, 1993; Dewick, 2009), and garlic is one of the promising sources of plant-derived natural products (Stoll, 2000). Garlic (*Allium sativum* L.) is widely used as a spice for human food worldwide, indicating its high safety margin for mammals. Garlic volatile oil has been shown to have insecticidal, repellent, antifeedant, antibacterial, nematocidal, and acaricidal properties (Stoll, 2000). Its essential oils were shown to possess insecticidal action (Isman, 2000; Stoll, 2000). The relative toxicity of garlic oil to young adults and larvae of the house fly, *Musca domestica* Fabr., and *Trogoderma granarium* Everts has been reported by Abdelbagi et al. (2018) and Okoro et al. (2023). Further, garlic has been reported to have medicinal, antibacterial, anthelminthic, antiprotozoal properties, hypoglycemic action, and hypolipidemic effects (Stoll 2000; EL-Shewehy et al., 2023).

Previous studies worldwide, and particularly in the Sudan in 1998, reported the promising potential of garlic oil as a fumigant for the control of stored-product pests. The fumigant action of garlic oils was evaluated against major storage pests in the Sudan (Shaaya et al., 1997; Elaissi et al., 2012). The research indicated that the Black-eyed cowpea weevil and other bruchids are more sensitive to garlic fumigation than other stored-product pests (Demeter et al., 2021). Therefore, it is necessary to validate their findings in larger chambers with greater seed quantities.

Thus, the current study aimed to validate the efficacy of steam-distilled Sudanese garlic (Cultivar Dongola) extract against *C. maculatus* (F.) under semi-storage conditions. This study also aims to confirm the previous findings and provide further evidence of the efficacy of garlic oils as control agents of the most important stored legume pests. The purpose of the laboratory study was to determine the fumigant efficacy of *Allium sativum* L. essential oils (EOs) against adults of *C. maculatus* (F.).

MATERIALS AND METHODS

Insect stock collection

Infested cowpea seeds used for culture were obtained from the Omdurman crops market and placed in a five-liter plastic jar one-fourth filled with the media (Cowpea seeds) as an adult rearing medium under growth conditions at 30 ± 2 °C and 60 ± 5% relative humidity. Jars were covered with muslin cloth fitted with rubber bands (Rup, 1984) and labeled with source and date. Four weeks later, the culture was sieved, the older adults were removed, and the newly emerged adults (0–3 days old) were collected and used for bioassay.

Preparation of insect culture

The culture media (cowpea seeds) were sterilized by heating to 120 °C for 15 minutes in an oven to destroy any infestation present (Winks, 1982). The sterilized media were stored at 30 ± 2 °C and 60 ± 5% relative humidity for use as culture media for experimental purposes.

Garlic clove powder preparation

The plant essential oils used in this study were selected based on their insecticidal activity reported in the literature against stored-product pests and other field pests. Sudanese garlic (cultivar Dongola) was obtained from the local market (Al-Shabi market, Sudan). Collected cloves were cleaned, sliced, and dried in the dark room for 10 to 20 days in October 2021. The dried garlic was ground into a fine powder with the kitchen grinder "Moulinex LM2B2126". The obtained powder was subjected to steam distillation (Figure 1).

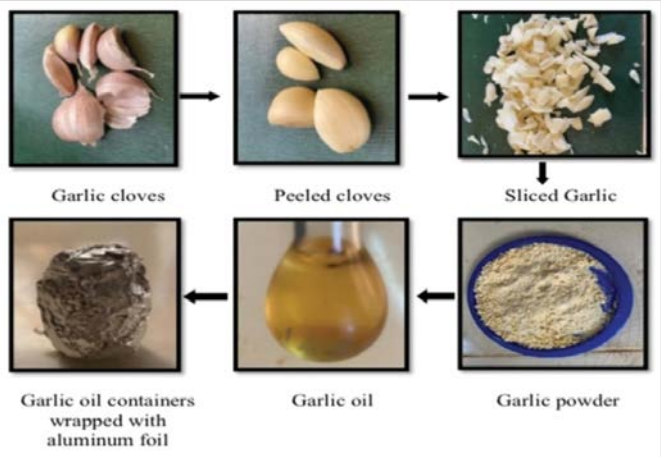


Figure 1. Drying of garlic cloves and steam distillation of oils

Steam distillation

Steam distillation was performed according to the method described by Chemat and Boutekedjiret (2015). A 300 g amount of garlic powder was placed in a 5 L round-bottom flask, and 1.5 L of distilled water was added. The mixture was manually stirred for 20 min before steam distillation. The content was subjected to steam distillation at 65-70 °C for 3 hours. The clear, yellow, volatile oil was distilled and collected in glass containers wrapped with aluminium foil, then stored in a refrigerator at 4 °C for bioassay (Mahgoub et al., 2015).

Bioassays

Fumigation in muslin cloth cups

The fumigation bioassay is considered applicable for stored product pests. The fumigation was performed in a closed chamber (50 × 50 × 50 cm^3) and used as an airtight fumigation method for the muslin-cloth-covered cups (capacity 300 ml). A 1 kg bag was filled with cowpea seeds. Different concentrations (0.001, 0.005, 0.01, 0.05, 0.1, and 1%) of garlic volatile oil were prepared by serial dilution with 99% v/v absolute ethanol. As much as 2 ml of oil at each concentration was placed in plastic cups (capacity 20 ml), which were covered with muslin cloth fitted with rubber bands to prevent insects from falling into the oil. Adults of *C. maculatus* (F.) were exposed to garlic oil vapors for one week. Twenty-five adults were released into the muslin-covered cups. Infested cowpea seeds, kept in muslin-covered cups, were placed into airtight fumigation chambers. The plastic cups containing the oil were placed into the fumigation chambers, which were then closed with transparent linoleum sheets and sealed with adhesive tape for a week. Insects in the control chambers were exposed to 2 ml of 99% absolute ethanol, while those in the standard treatments were exposed to one pellet (1 g) of Phostoxin® (aluminum phosphide). The chamber was kept at 30 ± 2 °C and 60 ± 5% relative humidity. Experimental units were arranged in a Completely Randomized Design (CRD) with three replicates. Examinations of the number of dead and alive insects were recorded during the incubation period, along with observations of deformation. Dead beetles were subjected to recovery tests.

Fumigation in jute sacs

The fumigation bioassay is considered applicable for stored product pests. The fumigation was performed in a closed chamber (50 × 50 × 50 cm^3), which was used as an airtight environment for fumigation of small jute sacs (1 kg) filled with cowpea seeds. Different concentrations (0.001, 0.005, 0.01, 0.05, 0.1, and 1%) of garlic volatile oil were prepared by serial dilution using 99% v/v absolute ethanol. A 2 ml sample from each concentration was placed in 20 ml plastic cups covered with muslin

cloth secured with rubber bands to prevent insects from falling into the oil. Twenty-five adults were released into the jute sacs. Tested beetles were exposed to garlic oil vapors for one week inside cowpea seed-filled jute sacs. Infested cowpea seeds, whether in muslin-covered cups or jute sacs, were placed into airtight fumigation chambers. Insects in the control chambers were exposed to 2 ml of 99% absolute ethanol, while those of the standard treatments were exposed to one pellet (1 g) of Phostoxin® (aluminum phosphide). The chamber was kept at 30 ± 2 °C and 60 ± 5% relative humidity. Experimental units were arranged in a Completely Randomized Design (CRD) with three replicates. Examinations of dead and live insects were recorded during the incubation period, noting any deformation or abnormalities. Dead beetles were subjected to recovery tests.

Recovery tests

At the end of the fumigation period, the dead beetles were transferred to Petri dishes containing a natural diet (uninfected cowpea seeds) for a four-day recovery period. Final mortality was recorded after observing the beetles during the four-day recovery period on the natural food. Dead beetles were identified as those that failed to move when touched or gently pressed with a blunt needle (Winks, 1984).

Statistical analysis

To compare the fumigant activity of garlic oils based on the final mortality of *C. maculatus* (F.) settled on treated and untreated groups, an analysis of variance (ANOVA) was conducted, and means were separated using LSD. Mortality data were further analyzed using probit analysis in MINITAB, version 13.20. Control mortality was corrected by Abbott's correction formula as follows:

$$P_t = ((P_o - P_c) / (100 - P_c)) \times 100, \text{ where:}$$

P_t is the percentage of control mortality, P_o is observed mortality, and P_c is control mortality (all in %).

RESULTS

Mortality rate of Callosobruchus maculatus

The final mortality during the direct exposure period of test insects to the volatile fumigant action of garlic oils in muslin-covered cups is shown in Table 1. Mortality increased significantly with increasing concentration, was observed among the test insects compared to the control. Mortality rates ranged from 22% to 100%, caused by doses from 0.001% to 1%, respectively. The highest concentration tested resulted in 100% mortality, similar to the standard Phostoxin® (aluminum phosphide) on treated insects. Concentrations of 0.1% and 0.05% caused mortalities of 86% and 82%, respectively.

On the other hand, the bioassay in jute sacs showed a very similar mortality rate, ranging from 20% to 100%, with doses from 0.001% to 1% (Table 2). The doses of 0.1% and 0.05% caused 82% and 80% mortality, respectively. The results showed that the tested concentrations of 0.1% and 0.05% did not significantly differ between the two bioassays, muslin-covered cups and jute sacs (Tables 1 and 2). The highest tested dose resulted in 100% mortality, like the bioassay with muslin-covered cups and the standard Phostoxin® (aluminum phosphide).

Figure 2 illustrates the comparative efficacy of garlic oils and Phostoxin® (aluminum phosphide) against cowpea beetles *C. maculatus* (F.), demonstrating a clear concentration-dependent increase in mortality after one week of exposure in muslin cloth-covered cups.

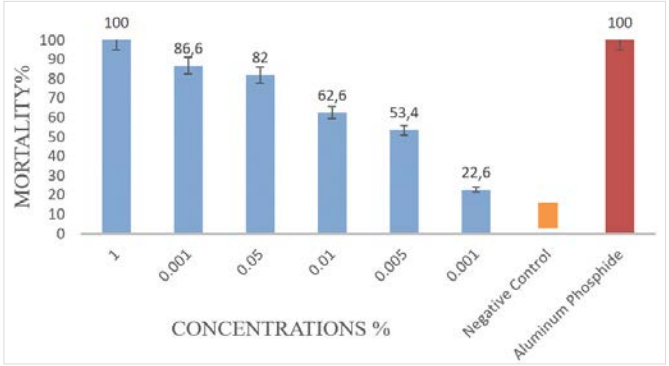


Figure 2. Comparative efficacy of garlic oil versus phosphine against cowpea beetles (*Callosobruchus maculatus* F.), showing mortality percentages at different concentrations after one week of exposure in muslin cloth-covered cups

Table 1. Mean values of final mortality data of *C. maculatus* (F.) adults exposed to vapors of garlic volatile oils in muslin cloth-covered cups

Concentrations (%)	No of test insects	Average number of dead insects*	Mortality (%)
1	25	9.09[a]	100
0.1	25	6.12[b]	86.6
0.05	25	5.94[b]	82
0.01	25	5.33[c]	62.6
0.005	25	5.08[c]	53.4
0.001	25	4.25[d]	22.6
Negative control (99% ethanol)	25	4.11[e]	18
Phostoxin® (standard treatment)	25	10[a]	100
LSD		0.15	
SE ±		0.08	

* The results were reported after watching recoveries in regular diets for four days. Means having different superscript letters in the column are significantly different at $P = 0.05$. LSD - Least significant difference; SE - standard error.

Table 2. Mean values of final mortality data for *C. maculatus* (F.) adults exposed to vapors of garlic volatile oils in jute sacs

Concentrations (%)	No of test insects	Average number of dead insects*	Mortality (%)
1	25	8.09[a]	100
0.1	25	5.94[b]	82.6
0.05	25	5.92[b]	80
0.01	25	5.25[c]	60
0.005	25	4.85[d]	44
0.001	25	4.15[e]	20
Negative control (99% ethanol)	25	4.03[e]	16
Phostoxin® (standard treatment)	25	9.09[a]	100
LSD		0.25	
SE ±		0.15	

* The results were reported after watching recoveries in regular diets for four days. Means having different superscript letters in the column are significantly different at $P = 0.05$. LSD - Least significant difference; SE - standard error.

The graphical representation confirms that higher concentrations of garlic oil achieved mortality levels comparable to those of Phostoxin® (aluminum phosphide), particularly at the highest tested concentration, where complete (100%) mortality was recorded.

Response related to dose

The mortality response was uniformly distributed across the entire dosage range and was, therefore, subjected to probit analysis. The log-dose probit data of the adults *C. maculatus* (F.) fumigated with garlic oils of various doses are displayed in Table 3 and Figure 3. Results showed that the responses to exposure of volatile garlic oils in muslin cloth-covered cups and jute sacs are almost parallel and not significantly different. Based on LC_{50} values, muslin cloth LC_{50} 6.54 × 10^{-4} mg/l and jute sacs LC_{50} 6.95 × 10^{-4} mg/l, on the other hand, depending on LC_{90} values muslin cloth was LC_{90} 1.01 × 10^{-4} mg/l and jute sacs LC_{90} 1.38 × 10^{-4} mg/l. However, the results of muslin-cloth-covered cups are superior to those of jute sacs, related to the line slopes, which ranged from 0.985 to 0.988. Both line slopes are steep, indicating a good homogeneity of the test population. The chi-square is small, ranging from 2.36 to 3.2, indicating good execution of the experiment, as shown in Table 3 and Figure 3.

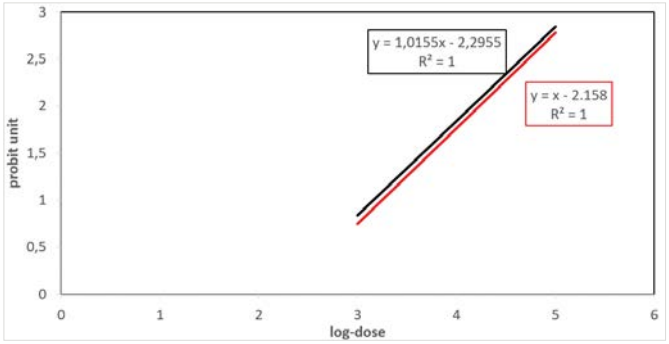


Figure 3. Probit lines of dose response of *C. maculatus* (F.) adults exposed to vapors of garlic volatile oils in muslin cloth-covered cups and jute sacs (the red line indicates muslin-covered cups; the black line indicates jute sacks)

Effect of garlic oil fumigation on the self-injurious behavior of test insects

The number of injured beetles caused by exposure to garlic vapor is shown in Table 4. Different concentrations resulted in significantly different numbers of injured insects compared to the control. In most cases, the effect is positively related to the dose at lower concentrations but negatively related at higher concentrations (Table 4). The self-injurious behavior was observed only in jute sacs. It included missing antennae or legs, with the number of missing antennae being greater at low doses and the number of missing legs higher at higher doses (Table 4).

Table 3. Concentration response of *C. maculatus* (F.) adults exposed to vapors of garlic volatile oils in muslin cloth-covered cups and jute sacs

Treatment	Lethal concentrations (mg/l)		Fiducial limit		Slope	D.F	Chi-square
			Lower	Upper			
Cups	LC_{10}	4.36 × 10^{-4}	4.87 × 10^{-4}	6.23 × 10^{-4}			
	LC_{50}	6.54 × 10^{-4}	3.42 × 10^{-4}	7.07 × 10^{-4}	0.985	4	2.360
	LC_{90}	10.01 × 10^{-4}	6.36 × 10^{-4}	10.91 × 10^{-4}			
Jute sacs	LC_{10}	3.06 × 10^{-4}	7.55 × 10^{-4}	8.17 × 10^{-4}			
	LC_{50}	6.95 × 10^{-4}	4.83 × 10^{-4}	9.56 × 10^{-4}	0.988	4	3.212
	LC_{90}	10.38 × 10^{-4}	6.63 × 10^{-4}	10.86 × 10^{-4}			

F.L = fiducial limits at 95% confidence
D.F = Degrees of freedom
LC_{10} = Lethal Concentration (mg/l) that can kill 10% of the population
LC_{50} = Lethal Concentration (mg/l) that can kill 50% of the population
LC_{90} = Lethal Concentration (mg/l) that can kill 90% of the population
Par = Parameters
Treat = Treatment.

Table 4. Average number of injured insects observed after seven days of exposure to garlic oil vapor

Concentrations (%)	Cups		
	Average number of injured insects*	Removed antennae	Removed legs
1	0.33[c]	0	0
0.1	1[b]	0	0
0.05	1.66[b]	0	0
0.01	3.33[a]	0	0
0.005	3[a]	0	0
0.001	4[a]	0	0
Negative control (99% ethanol)	1.33[c]	0	0
Phostoxin® (standard treatment)	0	0	0
LSD	1.41	0	0
SE ±	0.85	0	0

* Values followed by the same letter are not significantly different at $P = 0.05$

Recovery of treated beetles

Table 5 shows the average number of recovered beetles after four days on a natural diet. Results showed few cases of recovery. Recovery cases occur at the lowest three doses in cups and the lowest four doses in jute sacs.

Table 5. The average number of fumigated beetles recovered after observing for over four days on a natural diet

Concentrations (%)	Average number of recovered beetles	
	Cups	Jute sac
1	0	0
0.1	0	0
0.05	0	0
0.01	0	0
0.005	0.66[a]	0.66[a]
0.001	0.66[a]	0.66[a]
Negative control (99% ethanol)	0.33[a]	0.66[a]
Phostoxin® (standard treatment)	0	0
LSD	1.06	1.23
SE ±	0.61	0.70

* Values followed by the same letter are not significantly different at $P = 0.05$

DISCUSSION

The current study was carried out to investigate the efficacy of steam-distilled garlic volatile oil (extract from the Dongola cultivar) as a fumigant against the adult stage of the cowpea beetle, *C. maculatus* (F.), under semi-storage conditions. Results of the test carried out in muslin-cloth-covered cups indicated that steam-distilled volatile oils exerted significant, dose-related mortality among test beetles compared to the control. The final mortality ranged from 22% to 100% across the tested concentrations (0.001–1%), with the highest concentration producing complete (100%) mortality, comparable to the standard phosphine treatment. Concentrations of 0.1% and 0.05% exerted 86% and 82% mortalities, respectively. On the other hand, exposure to volatile oils in jute sacs resulted in significantly higher mortality among the tested beetles than in the control. The final mortalities ranged from 20% to 100% across the dose range of 0.001% to 1%, with the highest concentration tested (1%) causing 100% mortality, similar to the standard phosphine (as Phostoxin® tablets) treatment. Concentrations of 0.1% and 0.05% caused 82% and 80% mortalities, respectively. Garlic contains a variety of bioactive compounds, including allicin, alliin, and others, which contribute to its wide range of biological effects. Along with protective effects against various insects, these substances have antioxidant and anti-inflammatory effects and are associated with reduced risk of diseases, including cardiovascular diseases, cancer, and digestive issues (Gao et al., 2024). Furthermore, garlic is a promising natural source for developing functional foods or nutraceuticals for insect prevention and disease management (Gao et al., 2024).

Garlic volatile oil has a repellent effect against stored-product pests such as the maize weevil and the red flour beetle (Rahman and Motoyama, 2000). Garlic essential oil exhibits insecticidal, repellent, antifeedant, and developmental inhibitory activities against the insect *Tribolium castaneum* (H.) (Chaubey, 2013). Garlic oils and their constituents, especially diallyl disulfide, have insecticidal activity against the mealworm beetles *Tenebrio molitor* (L.) (Plata-Rueda et al., 2017a). Garlic has insecticidal, antibacterial, nematocidal, acaricidal, and other properties against all life stages of the *Aedes aeqypti* (L.) mosquito Singh and Singh, 2008; Dusi et al., 2022). Garlic (*Allium sativum* (L.) is widely used as a spice in human food worldwide, indicating its high safety margin to mammals (Prowse et al., 2006). Further, garlic oil was reported to have insecticidal effects that varied across different life stages of *Delia radicum* (L.) and *Musca domestica* (L.). LC_{50} values were provided for each life stage, indicating the doses required to kill 50% of the population. Garlic oil showed a mortality rate comparable to that of the organophosphate pesticide Birlane, suggesting its potential as a naturally derived insecticide (Prowse et al., 2006).

Further studies (Abdelbagi et al., 2018b) indicated that the ready-made Egyptian garlic oil was effective and caused significant mortality in adults of *Bruchidius incarnatus* (Boh) and *C. maculatus* (F.). The results indicated that both pests were susceptible to garlic oil vapors, with 100% mortality within 24 hours. The evaluation of the insecticidal activity, and the ovicidal and oviposition-al inhibitory effects of garlic volatile oils from Chinese, Egyptian, and Sudanese cultivars against *C. maculatus* (F.) was reported (Ahmed et al., 2019). Similar effects on insecticidal activity, ovicidal, and ovipositional inhibitory effects of volatile garlic oils (from Chinese, Egyptian, and Sudanese cultivars) against the faba bean beetle *B. incarnatus* (Boh) indicated that these volatile oils were found effective against the test insects and caused significant mortality compared to the control (Azhari et al., 2018). Probit analysis of both muslin cloths covered cups and jute sacs indicated that increasing exposure periods increase the efficacy (decrease LC_{50} and LC_{90} values) and improve the homogeneity of responses as indicated by the progressive decrease in LC_{90}/LC_{50} ratio, increase in steepness of LC-P Lines (i.e., increase in line slopes), and decrease in the fiducial limits. These findings are consistent with those of Elaziz et al. (2014), who reported that increasing the pre-accumulation period, which indicates greater exposure, results in better efficacy. The exposure

period-related increase in efficacy was also reported by (Elaziz et al., 2014; Mahgoub et al., 2015; Mahgoub et al., 2017). Contrary to the results of previous studies (Mahgoub et al., 2015; Mahgoub et al., 2017), probit analysis showed that the response of exposure of *C. maculatus* (F.) adults to the vapors of volatile garlic oils in muslin cloth-covered cups is almost like that of jute sacs, as indicated by their similar slopes. The discrepancy from the previous results (which showed a superior effect in cups compared to jute sacs) may be explained by differences in experimental conditions (larger chambers and larger sacs) and/or by the strain of the test insect. The steep line slopes of both cups and sacs indicate a high degree of homogeneity in the test population. The chi-square statistics are small, indicating good execution of the experiment.

The current study validated the reported efficacy of the steam-distilled Sudanese garlic (cultivar Dongola) extract against *C. maculatus* (F.) under semi-storage conditions. These results confirmed previous findings of the high sensitivity of bruchids to garlic's fumigant action. They provided additional evidence of the promising efficacy of garlic oils as control agents for the most important stored legume pests and called for further assessment of other bruchids under real storage conditions. The various concentrations of garlic oils gave significantly different numbers of injured beetles compared to the control. In most cases, the effect is positively related to dose at lower concentrations, while it is negatively related at higher concentrations. This can be explained by the proposal that lower concentrations may be sufficient to cause injury, while higher concentrations may be directly lethal (Plata-Rueda et al., 2017b; Muturi et al., 2018).

The study concluded that indigenous botanical powder and essential oil extracts are effective protectants against the cowpea bruchids, reducing grain damage and improving germination percentage without affecting weight loss (Asawalam and Anaeto, 2014). Injury cases were observed only in jute sacs and included removed antennae or legs. Generally, the number of removed antennae is greater at low doses, while the number of removed legs is greater at higher doses. Similar results were noticed by Rajabi (2020). Osekre and Ayertey (2004) reported that coconut oil and two types of palm oils were effective in controlling cowpea beetles on stored cowpea seeds, finding that oil treatment reduced oviposition and progeny emergence, with palm oil being superior and with no adverse effect on seed viability, suggesting its potential use by small-scale farmers. Recovery cases among fumigated insects occur at the lowest three doses in cups and the lowest four doses in jute sacs. This is expected, since high doses cause direct kill, while insects exposed to low doses may recover, as they might be exposed to sublethal doses of the toxic vapors.

CONCLUSION

The results of this study clearly show that steam-extracted garlic oil is a strong fumigant against the cowpea beetle, *Callosobruchus maculatus* (F.), when stored in a semi-storage setting. Garlic oil vapors caused many adult beetles to die at different concentrations (0.001% to 1%). The highest doses (1%) killed all of them within a week, which is the same as the standard phosphine treatment. The muslin-cloth-covered cups and the jute-sack bioassays both showed that garlic oil is effective at killing insects under various storage conditions. Probit analysis showed that *C. maculatus* (F.) is very sensitive to garlic oil. The LC_{50} mg/l values for muslin cloth and jute sacks were 6.54×10^{-4} and 6.95×10^{-4} mg/l, respectively. The steep dose-response slopes showed that the population was homogeneous. These results confirm earlier laboratory studies on garlic essential oil's effectiveness and show that it works in larger, semi-storage settings as well. Steam-extracted garlic oil is a promising, eco-friendly alternative to synthetic fumigants for controlling pests in stored cowpeas because it is effective, derived from nature, and has a proven safety record. Using it could help people rely less on chemical pesticides, lower health and environmental risks, and promote sustainable storage methods in places where cowpea is an important food source. To protect stored grain in the future, it will probably be necessary to combine both methods into full pest management programs. Because garlic oil is derived

from nature and works against many types of pests, it is ideal for routine preventive treatments. Phosphine is only for emergencies or pest populations that resist other treatments. This combined method leverages both fumigants' strengths while mitigating their individual weaknesses. As scientists work to improve the production and use of natural fumigants, garlic oil and other plant-based alternatives may become more popular than synthetic fumigants in business settings. The scientific evidence is clear: effective pest control does not have to put people or the environment at risk. This points to a future in which natural solutions play a larger role in keeping food safe around the world.

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