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EFFICACY OF SLOW-RELEASE ESSENTIAL OIL PELLETS ON THE PRE-OVIPOSITION BEHAVIOR OF *CALLOSOBRUCHUS MACULATUS* WITHIN CONTROLLED FUMIGANT CHAMBERS IN LAFIA, NIGERIA

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Abstract

This study evaluated the effectiveness of slow-release pelletized edible essential oils clove (*Syzygium aromaticum*), West African black pepper (*Piper guineense*), and ginger (*Zingiber officinale*) alongside a synthetic insecticide (Coopex® Dust) against *Callosobruchus maculatus*, a major pest of stored cowpea seeds. The experiment, conducted under controlled laboratory conditions (fumigant chamber) at the Federal University of Lafia, used a pre-oviposition bioassay with doses of 0.25, 0.5, 0.75, and 1.0 g per 50 g seeds, plus a control. Storage devices tested included polypropylene sacks, clay pots, jerry cans, and galvanized tins in a 4×5×4 factorial design, completely randomized with three replications. Data were transformed and analyzed using Statistix 10. Significant differences ($P \leq 0.05$) occurred in egg deposition: Where control treatment of ginger at 0.0 g recorded the highest egg count (535.00), followed by clove SRPEEO control treatment (527.92) at 0.0 g, while ginger-treated seeds at 1.0 g had the lowest (393.50). The highest adult mortality rate was observed with cowpea seeds treated with ginger (0.1 %) at 1.0 g, while the lowest mortality (0.01 %) was observed in seed treated with ginger at 0.0 g. Significant difference was seen in the interactive effect on storage devices and treatments where, Cowpea stored in PS and treated with Coopex had the highest percentage of insect emergence (68.41 %) while cowpea stored in GT treated ginger has the lowest adult emergence (47.65 %). The findings of this study underscore the potential of integrating botanical essential oils with hermetic storage technologies as an eco-friendly, cost-effective alternative to synthetic pesticides for sustainable cowpea storage.

Keywords: Storage devices, slow-release pelletized edible essential oils, clove, ginger, West African black pepper, Coopex® dust, Fumigant chamber.

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INTRODUCTION

Cowpea (*Vigna unguiculata* (L.) Walp.) is a vital leguminous crop extensively grown across sub-Saharan Africa, with Nigeria serving as a major production hub. It provides both an affordable protein source and an important stream of income for millions of rural households (Abebe and Alemayehu, 2022). Despite its nutritional and economic significance, production is often undermined by serious post-harvest constraints, particularly infestation by the cowpea weevil (*Callosobruchus maculatus* F.). This storage pest is highly destructive, capable of causing yield losses of up to 60% within a few months of storage if unchecked. Its fast reproductive rate and capacity to infest stored grains make it a persistent threat to both quality and quantity of cowpea harvests (Akah and Onyeka, 2017). Although synthetic insecticides are commonly used to curb these losses, their reliance comes with considerable drawbacks, including environmental hazards, risks to human and animal health, the evolution of resistant pest strains, and limited affordability for resource-constrained smallholder farmers (Samayoa *et al*., 2021).

Given these challenges, attention has shifted toward safer, eco-friendly pest management practices. Plant-derived essential oils (EOs) have gained prominence as promising alternatives, due to their insecticidal, repellent, and oviposition-deterring activities (Kostyukovsky *et al*., 2002). EOs are complex mixtures of volatile compounds extracted from aromatic plants, and their effectiveness against a wide range of insect pests is well established. For example, oils obtained from *Ocimum basilicum* (Basil), *Cymbopogon citratus* (lemongrass), and *Syzygium aromaticum* (clove) have demonstrated suppressive effects on *C. maculatus* infestations, highlighting their potential as natural grain protectants (Adedire *et al*., 2021). However, their practical application is often hindered by high volatility and rapid degradation, which shorten their effective duration and necessitate repeated application. To overcome these drawbacks, recent innovations have explored slow-release EO technologies—such as pelletized formulations—that enable a steady release of active constituents, thereby prolonging their protective effects against storage pests (Onwuka and Nelson, 2020; Rana *et al*., 2021).

One approach for evaluating the efficiency of such treatments involves pre-oviposition bioassays, which examine how interventions affect insect reproduction before eggs are deposited. These assays are useful for assessing the extent to which treatments reduce egg-laying, lower fecundity, and ultimately limit pest population growth (Musa and Olayemi, 2013). For *C. maculatus*, this technique is particularly valuable in identifying the potential of slow-release EO pellets to protect cowpea during the initial storage phase (Oyelami *et al*., 2022). Controlled laboratory setups, such as fumigation chambers, provide the precision necessary to reliably assess these effects. Previous investigations, for example, have shown that several essential oils significantly increased mortality and repellency of *C. maculatus* under laboratory trials (Panhwar *et al*., 2023). Similarly, Sabour and El-Aziz (2022) reported that slow-release EO formulations provided strong bio-insecticidal and grain-protective outcomes against *C. maculatus* and *C. chinensis*. Findings by Brito *et al*. (2022) highlighted not only insecticidal properties but also inhibition of detoxification enzymes in pulse beetles, further illustrating the diverse bioactivity of EO-based treatments.

In Nigeria, where cowpea remains a staple food and pest-induced post-harvest losses are a pressing issue, slow-release EO pellets stand out as a promising sustainable control measure. Recent research has emphasized the value of locally available botanicals for developing effective, low-cost, and environmentally benign pest management strategies. For instance, Ayinde *et al*. (2022) demonstrated the insecticidal potential of volatile oils derived from *Rosmarinus officinalis* and *Callistemon viridis* against *C. maculatus*, while Awojide *et al*. (2023) reported significant activity of *Monodora myristica* oil against multiple storage insect pests. Such findings support the integration of indigenous plant resources into EO-based formulations. Against this background, the present study investigates the pre-oviposition deterrent capacity of slow-release essential oil pellets against *Callosobruchus maculatus* under laboratory conditions in Lafia, Nigeria. By evaluating their effects on key reproductive parameters, this work seeks to advance eco-sustainable storage protection strategies that not only safeguard food supplies but also improve the livelihoods of smallholder farming communities in the region.

MATERIALS AND METHODS

The research was conducted in the Agronomy Laboratory at the Federal University of Lafia, located in the Southern guinea Savanna agro-ecological zone of Nigeria. The specific coordinates of the study site are 8°30′22″N and 8°31′22″E (Jayeoba, 2013). The cowpea seed bruchid (*C. maculatus*) was collected from already infested cowpea. These insects were cultured in glass jars filled with pristine cowpea seeds to create a pure inoculum for the experiment. The culture was maintained for five generations to ensure that the insects were acclimatized before the experiment commenced. The cowpea variety, Kananado was purchased from the Lafia main market, Nasarawa State, and was put in the freezer (-18 ^{0}C) after sorting to disinfest it against any inherent eggs or larva in the seed. After five days, the seeds were equilibrated to laboratory conditions and stored in Kilner jars until use. The storage devices, jerry cans (1 tr), sewn polypropylene sacks (5 X 5 cm with a zip lock), galvanized tins (250 g size), and clay pots with cover (500 g size) were purchased from the Lafia main market. Each device was modified to standard dimensions suitable for the experiment. The slow release pelletized edible essential oils made from clove, ginger, and West African black pepper were procured from the National Institute for Pharmaceutical Research and Development (NIPRD) in Abuja and the synthetic insecticides was obtained from the Food and Storage Reserve Department of the Federal Ministry of Agriculture and Food Security, Lafia Office, Nigeria. The experiment was laid out in a completely randomized design with three replications.

Pre-oviposition application of Slow Release Pelletized Edible Essential Oils.

In this bioassay, 50 g of the cowpea legume variety Kananado were weighed into different storage devices viz: clay pots, jerry cans, polypropylene sacks and galvanized tins and treated with 0.0, 0.25, 0.50, 0.75 and 1.0g of each slow release pelletized edible essential oil and Coopex® dust a synthetic insecticide. These treatments were allowed to remain in place for 10 days. After 10 days; twenty pairs of 3-day old adults of *C. maculatus* was introduced into each storage devices with treatments after airing the grain contents for 2 hours and are kept in inside a fumigant chamber. The gravid female bruchids was allowed to lay eggs for 10 days. On day 10, the fume valve was released and the insects were removed from all treatments and all the eggs laid in each treatment was counted and recorded. The study was laid out in a 4x5x4 factorial experiment in a Completely Randomized Block Design (CRBD) with three (3) replications for each treatment, dosage concentrations and storage devices. Data were collected to monitor bruchid emergence by following these procedures: All adults that emerged in all the treatments were counted and recorded. Adult mortality was calculated based on actual physical mortality of the adults' insect at the time of recording, Abbott's (1925) formula was used to calculate the effect of edible essential oil on the mortality of adult *C. maculatus* in comparison to the mortality recorded in the control as follows:

$$Pt = \frac{Po - Pc}{100 - Po} \times 100$$

Where:

Pt = Corrected mortality (%)

Pc=Control mortality (%)

Po =Observed mortality (%)

The number of adult insect emergence was expressed in percentages following the method of Odeyemi and Daramola (2000) as follows:

$$\%\text{Adult emergence} = \frac{\text{Total number of adult emergence}}{\text{Total number of eggs laid}} \times 100$$

Initial weight of each legumes sample was taken to determine percentage weight loss. The percentage weight loss was calculated following the method described by Ileke *et al.* (2020) as follows:

$$\text{Percentage weight loss (PWL)} = \frac{W_1 - W_2}{W_2} \times 100$$

Where

W_1 = Initial weight

W_2 = Final weight

Bruchid Perforation Index (BPI)

This was expressed as described by Fatope *et al.* (1995).

$$\text{BPI} = \frac{\text{\% treated cowpea grains perforated}}{\text{\% control cowpea grains perforated}} \times 100$$

BPI value exceeding 50 was regarded as enhancement of infestation by the beetle or negative protectability of the extract tested.

Statistical Analysis

All data obtained were subjected to two-way ANOVA to analyze the effects of different dosesof treatments and types of storage devices on measured outcomes. Date taken included Number of eggs laid by *Callosobruchus maculatus* in each treatment, Insect mortality rate recorded in percentages (%), Grain weight loss (%) and Bruchid Perforation Index.

Analysis was carried out using a Two-Way ANOVA involving **Treatment type/dose which** includes different slow-release pelletized edible essential oils (clove, West African black pepper, ginger) and the synthetic insecticide (Coopex® Dust) applied at varying doses (0.25 g, 0.5 g, 0.75 g, 1.0 g, plus control) and

Storage device types: Polypropylene sacks, Clay pot, Jerry can and Galvanized tins. Furthermore, the differences between treatment means were separated using the least mean significant difference test at $p < 0.05$ using STATISTIX 10 for students' version (2018) analytical package

RESULTS

Pre-oviposition interactive effects on treatments and concentrations on cowpea weevil and cowpea seed in Fumigant Chamber.

Table 1 presents the combined influence of treatment type and concentration of slow-release pelletized essential oils (SRPEEOs) on *Callosobruchus maculatus*. The outcomes revealed statistically significant variations ($p \leq 0.05$) in oviposition across treatments and doses. The maximum number of eggs (535) was obtained in cowpea seeds exposed to ginger SRPEEO at 0.0 g, followed closely by clove SRPEEO at 0.0 g (527). In contrast, the lowest egg deposition was recorded in seeds treated with 1.0 g of ginger SRPEEO (393.50) and Coopex® at the same dose (405.75).

Significant effects ($p \leq 0.05$) were also observed in adult mortality. Seeds treated with 1.0 g of ginger SRPEEO showed the highest mortality (0.10%), while the control treatments with clove and West African black pepper registered the lowest (0.01%). Differences ($p \leq 0.05$) in percentage adult emergence (PAE) were also evident. The greatest PAE was observed with ginger SRPEEO at 0.0 g (71.84%) and Coopex® at 0.0 g (71.19%). The lowest PAE occurred in seeds treated with 1.0 g of ginger (51.31%) and clove (51.43%).

Weight loss analysis also showed significant differences ($p \leq 0.05$). Clove SRPEEO at 0.0 g (70.99%) and Coopex® at 0.0 g (68.83%) caused the highest percentage weight loss (PWL), whereas West African black pepper at 1.0 g

(4.19%) and Coopex® at 1.0 g (4.63%) showed the lowest. Similarly, the weevil perforation index (WPI) differed significantly ($p \leq 0.05$). Clove SRPEEO at 0.0 g (93.21%) and West African black pepper at 0.0 g (92.17%) produced the highest values, while ginger SRPEEO at 1.0 g (62.00%) had the lowest.

Table 1: Pre-oviposition interactive effects on treatments and concentrations on cowpea weevil and cowpea seed in Fumigant Chamber.

Treatment	Concentration	No of Eggs Laid	Percentage Mortality	Percentage Adult Emerged	Percentage Weight Loss	Percentage Bruchid perforation index
Ginger	0.0	535.00^{a}	0.01^{a}	71.84^{a}	70.99^{a}	93.21^{a}
Clove	0.0	527.92^{a}	0.01^{a}	71.19^{a}	68.83^{ab}	92.17^{a}
WABP	0.0	523.83^{a}	0.01^{a}	67.18^{b}	67.94^{b}	85.49^{b}
Coopex	0.0	498.00^{b}	0.01^{a}	64.68^{c}	67.25^{b}	81.36^{c}
Coopex	0.25	482.42^{bc}	0.01^{b}	59.01^{d}	37.53^{c}	73.44^{d}
WABP	0.25	482.33^{bc}	0.02^{b}	58.40^{de}	33.51^{d}	72.70^{de}
Clove	0.50	475.17^{bcd}	0.02^{b}	57.88^{de}	27.73^{e}	71.84^{def}
Ginger	0.50	471.08^{cde}	0.02^{b}	56.65^{ef}	23.69^{f}	69.80^{efg}
Ginger	0.25	461.08^{cde}	0.05^{c}	55.86^{fg}	21.34^{fg}	69.14^{fg}
WABP	0.50	457.33^{def}	0.03^{c}	55.24^{fgh}	20.01^{gh}	67.97^{gh}
Clove	0.25	451.08^{efg}	0.03^{d}	55.23^{fgh}	18.38^{hi}	67.80^{gh}
Coopex	0.50	449.00^{efg}	0.04^{de}	54.61^{ghi}	16.80i	66.10^{ghi}
Clove	0.75	436.50^{fgh}	0.05^{ef}	53.82^{hij}	11.58^{j}	65.78^{hij}
Ginger	0.75	429.00^{ghi}	0.07^{fg}	53.40^{hijk}	10.11^{j}	65.22^{hijk}
Coopex	0.75	424.42^{hi}	0.07^{fg}	53.02^{ijkl}	10.09^{j}	64.50^{ijk}
WABP	0.75	415.00^{hij}	0.07^{g}	52.72^{ijkl}	9.78^{j}	64.09^{ijk}
Clove	1.0	407.50^{ij}	0.10^{h}	52.07^{jkl}	6.39^{k}	63.10^{jk}
WABP	1.0	406.08^{ij}	0.10^{h}	51.57^{kl}	5.15^{k}	62.34^{k}
Coopex	1.0	405.75^{ij}	0.10^{h}	51.43^{l}	4.63^{k}	62.09^{k}
Ginger	1.0	393.50^{j}	0.10^{h}	51.31^{l}	4.12^{k}	62.00^{k}
LSD		**24.07**	**0.0075**	**1.96**	**2.78**	**3.26**

Means with the same letter in the column are not significantly different at 5 % level of probability using LSD Test ($P \leq 0.05$). Where: BPI: Bruchid perforation Index. SRPEEO: slow release pelletized essential oil. PS: Polypropylene sack; CP: Clay pot; JC: Jerry can. GT: Galvanize tin, WABP: West African black pepper. Coopex®: Cypermethrin dust.

Pre-oviposition interactive effects on storage devices and treatments on cowpea weevil and cowpea seed in Fumigant Chamber.

Table 2 highlights the combined effects of storage containers and SRPEEO treatments on *C. maculatus* infestation. Marked variations ($p \leq 0.05$) in oviposition were detected among treatments and storage methods. The largest egg numbers were counted in polypropylene sacks with Coopex® (614.07) and in clay pots with clove SRPEEO (607.47). Conversely, the lowest oviposition was seen in galvanized tins treated with 1.0 g of ginger SRPEEO (248.40), followed by tins treated with 1.0 g of Coopex® (328.07).

Mortality rates also varied significantly ($p \leq 0.05$). The highest (0.06%) was observed in galvanized tins treated with ginger and clove SRPEEOs, while the lowest (0.04%) occurred in clay pots containing West African black pepper SRPEEO. Percentage adult emergence (PAE) likewise showed significant differences. The greatest PAE values were obtained from clove SRPEEO in polypropylene sacks (68.41%) and Coopex® in polypropylene sacks (68.24%). The lowest rates were recorded for West African black pepper SRPEEO (47.65%) and Coopex® (47.71%) stored in galvanized tins.

In terms of seed weight loss, clove SRPEEO in polypropylene sacks (40.93%) and ginger SRPEEO in the same sacks (39.75%) produced the highest PWL values, while ginger (15.76%) and clove (18.49%) stored in galvanized tins showed the least. The weevil perforation index (WPI) also differed significantly, with the highest values seen in clove SRPEEO stored in clay pots (85.32%) and polypropylene sacks (84.49%). The lowest WPI occurred in West African black pepper and Coopex® stored in galvanized tins (47.73% and 48.74%, respectively).

Table 2: Pre-oviposition interactive effects on storage devices and treatments on cowpea weevil and cowpea seed in Fumigant Chamber.

Storages/ Trt.	Treatment	No of Eggs Laid	Percentage Mortality	Percentage Adult Emerged	Percentage Weight Loss	Percentage Bruchid peroration index
PS	Coopex	614.07[a]	0.06[a]	68.41[a]	40.93[a]	85.32[a]
CP	Clove	607.47[a]	0.06[ab]	68.24[a]	39.75[ab]	84.49[a]
PS	Clove	607.20[a]	0.05[ab]	67.97[a]	37.55[bc]	83.51[a]
PS	WABP	598.73[ab]	0.05[ab]	67.41[a]	35.89[cd]	83.02[ab]
PS	Ginger	579.27[b]	0.05[abc]	63.06[b]	33.67[de]	80.20[bc]
CP	Ginger	555.73[c]	0.05[abc]	62.52[b]	32.05[e]	79.44[c]
CP	Coopex	554.00[c]	0.05[abc]	61.89[b]	28.09[f]	76.00[d]
CP	WABP	552.20[c]	0.05[abcd]	61.57[b]	26.19[f]	76.00[de]
JC	Clove	356.60[d]	0.05[abcd]	53.30[c]	21.91[g]	76.00[de]
JC	Ginger	352.67[d]	0.05[bcde]	52.86[c]	20.71[gh]	75.00[de]
GT	Clove	348.80[de]	0.05[cdef]	49.78[d]	20.44[gh]	73.00[ef]
JC	Coopex	335.73[de]	0.05[cdef]	49.14[de]	19.28[h]	70.73[f]
JC	WABP	335.73[de]	0.05[cdef]	48.33[de]	19.28[h]	50.89[g]
GT	WABP	330.93[e]	0.05[def]	47.84[e]	18.76[h]	48.74[gh]
GT	Coopex	328.07[e]	0.04[ef]	47.71[e]	18.49[h]	47.81[h]
GT	Ginger	248.40[f]	0.04[f]	47.65[e]	15.76[i]	47.73[h]
LSD		21.53	0.01	1.75	2.48	2.92

Means with the same letter in the column are not significantly different at 5 % level of probability using LSD Test (P≤0.05). where: WPI: Weevil perforation Index. SRPEEO: slow release pelletized essential oil. PS: Polypropylene sack; CP: Clay pot; JC: Jerry can. GT: Galvanize tin, WABP: West African black pepper. Coopex®: Cypermethrin dust

Pre-oviposition interactive effects on storage devices and concentrations on cowpea weevil and cowpea seed in Fumigant Chamber.

Table 3 demonstrates how storage devices and concentration levels of SRPEEOs interact to influence *C. maculatus* infestation. Statistically significant differences (p≤0.05) in oviposition were noted. The greatest egg deposition occurred in cowpea seeds stored in polypropylene sacks without SRPEEO (680.75) and in sacks with 0.25 g (642.75). By contrast, the fewest eggs were found in galvanized tins treated with 1.0 g (277.25) and jerry cans at 1.0 g (278.67).

Variation in adult mortality was also significant (p≤0.05). The highest mortality (0.10%) occurred in galvanized tins at 1.0 g, while the lowest mortality (0.01%) was associated with polypropylene sacks. Adult emergence percentages showed similar patterns. The highest PAE was observed in polypropylene sacks without treatment (78.83%), followed by clay pots at 0.25 g (69.65%). The lowest emergence was recorded in galvanized tins treated with 1.0 g (38.07%) and 0.75 g (40.41%).

Differences (p≤0.05) were also observed in percentage weight loss. The greatest losses were found in cowpea stored in clay pots at 0.0 g (81.56%) and polypropylene sacks at 0.25 g (80.72%). The least losses occurred in galvanized tins at 1.0 g (1.47%) and jerry cans at 0.75 g (4.18%). Similarly, the WPI values varied considerably. The highest were in polypropylene sacks at 0.0 g (93.29%) and 0.25 g (89.31%), while the lowest were in ginger-treated seeds at 1.0 g (33.41%) and cowpea in jerry cans at 1.0 g (36.92%).

Table 3. Pre-oviposition interactive effects on storage devices and concentration on cowpea weevil and cowpea seed in Fumigant Chamber.

Storage	Concentration	No of Eggs Laid	Percentage Mortality	Percentage Adult Emerged	Percentage Weight Loss	Percentage Bruchid peroration index
PS	0.0	680.75[a]	0.01[g]	78.83[a]	81.56[a]	93.29[a]
PS	0.25	642.50[b]	0.01[g]	69.65[b]	80.72[a]	89.31[b]
CP	0.0	619.33[bc]	0.01[g]	68.35[b]	62.13[b]	89.08[b]
PS	0.50	606.67[c]	0.01[g]	65.57[c]	50.60[c]	85.39[c]
CP	0.25	574.83[d]	0.02[b]	65.51[c]	49.98[c]	83.58[cd]
PS	0.75	566.08[d]	0.02[b]	64.12[cd]	33.51[d]	82.60[cde]
CP	0.50	552.58[de]	0.02[b]	63.16[de]	28.56[e]	80.60[de]
PS	1.0	538.33[ef]	0.03[c]	63.11[de]	26.11[e]	79.80[e]
CP	0.75	536.17[ef]	0.03[d]	61.93[ef]	19.98[f]	75.93[f]
CP	1.0	518.58[f]	0.04[de]	61.30[efg]	18.98[f]	74.74[fg]
GT	0.0	406.75[g]	0.04[de]	60.90[fg]	18.23[f]	74.62[fg]
GT	0.25	369.42[h]	0.04[e]	59.46[g]	12.45[g]	72.36[gh]
JC	0.50	350.67[hi]	0.05[f]	50.42[h]	10.35[gh]	70.50[h]
GT	0.50	342.67[i]	0.06[f]	50.13[h]	9.44[hi]	69.57[hi]
JC	0.0	341.00[i]	0.08[f]	50.06[h]	9.42[hij]	69.26[hi]
JC	0.25	327.08[ij]	0.08[f]	47.14[i]	7.23[ij]	67.08[i]
GT	0.75	309.42[jk]	0.10[g]	45.69[i]	6.65[jk]	51.86[j]
JC	0.75	293.25[kl]	0.10[g]	43.29[j]	4.37[k]	41.22[k]
JC	1.0	278.67[l]	0.10[g]	40.41[k]	4.18[kl]	36.92[l]
GT	1.0	277.25[l]	0.10[g]	38.07[l]	1.47[l]	33.41[m]
LSD		**24.07**	**0.01**	**1.97**	**2.78**	**3.26**

Means with the same letter in the column are not significantly different at 5 % level of probability using LSD Test ($P \leq 0.05$).

Where: WPI: Weevil perforation Index. SRPEEO: slow release pelletized essential oil. PS: Polypropylene sack; CP: Clay pot; JC: Jerry can. GT: Galvanize tin, WABP: West African black pepper. Coopex®: Cypermethrin dust

DISCUSSION

The findings of this research revealed that the three SRPEEOs tested Ginger, Clove, and West African Black Pepper (WABP) were effective in preventing pre-oviposition by adult *Callosobruchus maculatus* when applied with varying concentrations of Ginger, Clove, WABP, and Coopex. The treatments influenced adult mortality, egg deposition, adult emergence, seed weight loss, and the weevil perforation index (WPI) when used in different storage devices within a fumigant chamber. Notably, WABP, Ginger, Clove, and Coopex showed strong deterrent effects before infestation at all tested concentrations. These results corroborate the observations of Kalpna *et al*. (2022), who demonstrated that extracts of Zingiber officinale suppressed feeding and oviposition by C. maculatus.

Similarly, Nisar *et al*. (2022) reported that various essential oils, including Ginger and WABP, substantially reduced oviposition and increased beetle mortality at higher concentrations (e.g., 2.0 mL per 100 g of grain), confirming the broader principle that plant-derived oils can disrupt reproduction in stored-product pests. These findings also support the results of Sharma *et al*. (2021), which showed that higher doses of botanical insecticides amplified both repellency and toxicity. Comparable trends were reported by Tadele *et al*. (2020) and Ajayi *et al*. (2021), who found that increasing botanical concentrations impeded insect growth, disrupted larval development, and impaired respiratory functions.

The findings of this study corroborating with the conclusions of Tadele *et al*. (2020) and Zhang *et al*. (2021), which emphasized the pivotal influence of storage container type on treatment performance stating that polypropylene sacks performed the worst, with higher egg deposition, lower insect mortality, and greater seed damage likely due to their permeability, which facilitates pest entry and accelerates essential oil vapor loss. In contrast, findings from Simmonds *et al*. (2021) and Shuaib *et al*. (2022) align with this research, indicating that airtight containers such as galvanized tins and jerry cans retain the fumigant activity of botanicals for longer, thereby increasing mortality and reducing adult emergence. The use of galvanized tins in combination with higher botanical concentrations yielded the most substantial reduction in *C. maculatus* infestation, seed weight loss, and physical damage.

These results are further supported by Ferraz *et al*. (2024), who showed that closed fumigant chambers sustain essential oil vapors above lethal or behavior-modifying thresholds, thereby enhancing adult mortality, ovicidal and larvicidal effects, and oviposition deterrence. Likewise, the work of Donga and Baributsa (2023) confirms that hermetic storage suppresses bruchid activity through oxygen depletion and restricted gas exchange, complementing the fumigation effect of essential oils and extending the storage life of cowpea seeds.

CONCLUSION

Overall, this study highlights the high potency of Ginger, Clove, and WABP in reducing C. maculatus populations in stored cowpea. At higher application rates and when paired with suitable storage systems, these botanicals markedly improved adult mortality, curtailed egg laying, minimized adult emergence, reduced weight loss, and lowered WPI values. The results demonstrate that the effectiveness of botanical protectants is influenced both by concentration and by the permeability of the storage container. Airtight containers, such as galvanized tins and jerry cans, were the most effective in maintaining the repellent and toxic properties of essential oils, while more permeable sacks allowed rapid vapor loss and diminished protection.

Combining hermetic storage with high botanical concentrations offers a sustainable and eco-friendly alternative to chemical pesticides, safeguarding seed quality and prolonging storage duration. Thus, integrating botanical essential oils with improved storage technologies presents a practical pest management option for smallholder farmers and commercial grain storage operations. Further research should refine dosage levels, evaluate economic feasibility, and explore the combined use of multiple botanicals under diverse environmental conditions to promote adoption and scalability.

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