Dose-dependent insecticidal activity of wild basil (*Ocimum americanum* L.) against the cowpea seed beetle (*Callosobruchus maculatus* Fab.): Evidence for a locally sourced postharvest protectant in semi-arid Kenya

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ABSTRACT

Cowpea (*Vigna unguiculata* (L.) Walp) is a critical grain legume in sub-Saharan Africa, yet postharvest losses inflicted by the cowpea seed beetle (*Callosobruchus maculatus* Fab.) can reach 100% of stored grain, with weight losses up to 60%. Synthetic insecticides remain the primary control strategy despite documented human health and environmental risks, creating an urgent need for locally available, low-cost botanical alternatives. This study evaluated the dose-dependent insecticidal activity of *Ocimum americanum* (wild basil) leaf, flower, and whole-plant powders against *C. maculatus* in stored cowpea seeds, and characterized the concentration–mortality response across five dosage levels. This research was anchored on Botanical Insecticide Theory and Modes of Action, Dose–Response Theory, Phytochemical Variability Theory and Postharvest Loss Theory. Dried and ground plant materials (leaves, flowers, and whole mature plants) were applied to 10 g of disinfested cowpea seeds (variety KVU 27-1) at 0.5, 1.0, 2.0, 4.0, and 8.0 g per jar. Ten pairs of 1–3 day-old adult beetles were introduced per treatment. Controls included untreated seeds and Actellic® Super dust (pirimiphos-methyl). The experiment followed a completely randomized design with four replications. Adult mortality was recorded at 72 hours, and seed weight loss was measured at 90 days. Data were analyzed using generalized linear models with binomial and beta error structures, followed by non-linear concentration–response modelling and effective concentration (EC_{50}/EC_{90}) estimation. Leaf powder at 8.0 g produced 92.5% adult mortality (95% CI: 88.4–95.4%) and reduced seed weight loss to 3.0%. Leaf powder was the most efficacious plant part, followed by whole-plant and flower powders. Non-linear regression revealed a steep sigmoidal mortality response for leaf powder (EC_{50} = 3.1 g; EC_{90} = 6.8 g per 10 g seed). Actellic® Super dust achieved 100% mortality at all tested dosages. A strong negative exponential relationship between mortality and weight loss was observed (R^2 = 0.94). *Ocimum americanum* leaf powder at 8.0 g per 10 g seed (800 g kg^{-1}) provides effective, low-cost protection against *C. maculatus* and represents a viable biorational alternative to synthetic insecticides for smallholder farmers in semi-arid Kenya. The steep, predictable dose–response relationship supports the development of standardized botanical formulations for integrated postharvest pest management.

Keywords: Biorational control, cowpea seed beetle, dose–response, postharvest loss, *Ocimum americanum*, smallholder farming, semi-arid Kenya

I. INTRODUCTION

Cowpea (*Vigna unguiculata* (L.) Walp) is an annual herbaceous legume of the family Fabaceae, native to the drier regions of the world and widely cultivated across Africa, Latin America, Southeast Asia, and the southern United States (Liu et al., 2020; Remesh et al., 2025). The crop serves as a primary source of plant protein, with grains, leaves, green pods, and fresh peas all contributing to human nutrition (Gondwe et al., 2019). Beyond its nutritional value, cowpea plays a critical role in traditional cropping systems through atmospheric nitrogen fixation, contributing to soil fertility in smallholder farming systems where fertilizer inputs are minimal or absent (Kyei-Boahen et al., 2017). This dual role—nutritional and agronomic—positions cowpea as a cornerstone of food security in marginal production environments.

Africa accounts for approximately 84% of global cowpea production area, with over 80% of African output concentrated in West Africa (Food and Agriculture Organization of the United Nations Statistics [FAOSTAT], 2016). In Kenya, cowpea is the third most important grain legume after common bean and pigeon pea, covering approximately 24,431 hectares (Horticultural Crops Directorate [HCD] Report, 2016). The crop is particularly important in semi-arid regions where alternative protein sources are limited.

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Callosobruchus maculatus (Fabricius) (Coleoptera: Chrysomelidae; formerly Bruchidae), commonly known as the cowpea seed beetle or cowpea weevil, is the most destructive insect pest of stored cowpea (Legalov et al., 2020). Adults readily infest seeds in the field and can breed continuously in stored dry grain. Larvae burrow and feed on the endosperm and embryo, undergoing complete metamorphosis before emerging as winged adults. Severe infestations can affect 100% of stored grain and cause up to 60% weight loss within a few months (Mashela & Pofu, 2012). This level of loss is catastrophic for resource-limited farmers who depend on stored grain for household food security and income generation.

The predominant control strategy remains the use of synthetic insecticides, particularly carbamates, synthetic pyrethroids, and organophosphates (Jackai & Adalla, 1997). While effective, these chemicals present significant drawbacks: high potential for human toxicity, environmental contamination, development of pest resistance, and unacceptable residues in food products. Moreover, the cost of synthetic insecticides often exceeds the financial capacity of smallholder farmers, and access may be limited in remote rural areas. The increasing global demand for pesticide residue-free food (Dalavayi et al., 2021) has catalyzed interest in biorational alternatives derived from plants.

Botanical insecticides are extracted from various plant parts—leaves, stems, seeds, roots, bulbs, rhizomes, unripe fruits, and flower heads—and possess broad-spectrum activity, low cost, and ready availability (Dalavayi et al., 2021). They typically pose minimal health hazards and environmental pollution compared with synthetic compounds. *Ocimum americanum* L. (wild basil), a common weed in the drier parts of Kenya, is known by numerous local names across ethnic communities (e.g., *mutaa* in Kamba, *mutei* in Kikuyu, *gatherti/makori* in Meru), reflecting its cultural familiarity and accessibility (Charika et al., 2011). Studies have demonstrated that *O. americanum* extracts possess antimicrobial and insecticidal activities (Sulaiman et al., 2025; Belhamel et al., 2020), with eugenol identified as the major essential oil compound (28.46%), followed by methyl chavicol (17.34%) and terpineol (15%) (Sulaiman et al., 2025).

However, critical evidence gaps remain: (1) few studies have systematically compared the efficacy of different plant parts (leaves vs. flowers vs. whole plant); (2) concentration–mortality relationships have not been rigorously characterized using appropriate statistical models; (3) the quantitative relationship between adult mortality and seed weight loss has not been established; and (4) no study has estimated effective concentration values (EC_{50}, EC_{90}) to guide practical dosage recommendations.

1.1 Statement of the Problem

Despite the nutritional and agronomic importance of cowpea in sub-Saharan Africa, postharvest losses caused by *C. maculatus* remain a persistent and severe constraint on food security and household income. Infestation can destroy up to 100% of stored grain and cause weight losses of up to 60% within a few months (Mashela & Pofu, 2012). Smallholder farmers in semi-arid Kenya including Kitui, Mbeere, Tharaka-Nithi, Makueni, and Machakos are disproportionately affected because they lack access to reliable, affordable storage technologies and depend on retained seed and grain for household consumption and market sale. The conventional response application of synthetic insecticides such as pirimiphos-methyl (Actellic® Super) is increasingly problematic. Synthetic pesticides are costly, often unavailable in remote areas, and associated with human health hazards, environmental contamination, pesticide residues in food, and the development of pest resistance (Jackai & Adalla, 1997; Dalavayi et al., 2021). These concerns have intensified the search for safe, affordable, and locally available alternatives, particularly botanicals that farmers can collect and process themselves. Wild basil (*O. americanum*) is a common weed in the drier parts of Kenya and is widely recognized by local communities (Charika et al., 2011). However, despite anecdotal use by some farmers, its efficacy against *C. maculatus* has not been systematically quantified.

1.2 Study Objectives

1) To evaluate the dose-dependent insecticidal activity of leaf, flower, and whole-plant powders of *O. americanum* against *C. maculatus* across five concentration levels
2) To characterize concentration-mortality relationships using non-linear modelling
3) To quantify the relationship between adult mortality and seed weight loss
4) To compare efficacy with a standard synthetic insecticide.

II. LITERATURE REVIEW

2.1 Theoretical Review

Botanical Insecticide Theory and Modes of Action. Botanical insecticides are plant-derived secondary metabolites that exert toxic, repellent, antifeedant, or growth-regulating effects on insects. The theoretical foundation for

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their use rests on co-evolutionary plant–herbivore interactions, in which plants synthesize allelochemicals-alkaloids, terpenoids, phenolics, and flavonoids as chemical defenses against herbivory (Mann & Kaufman, 2012). In the Lamiaceae family, the principal bioactive constituents are monoterpenes and sesquiterpenes, notably eugenol, methyl chavicol, terpineol, farnesene, α-bisabolene, 1,8-cineole, and limonene (Sulaiman et al., 2025; Belhamel et al., 2020). These compounds are theorized to act through multiple, often synergistic, mechanisms: (i) neurotoxicity via inhibition of acetylcholinesterase, leading to nervous system dysfunction and death (Mann & Kaufman, 2012; Vladimir-Knežević et al., 2014); (ii) disruption of the respiratory system, causing asphyxiation (Vladimir-Knežević et al., 2014); and (iii) interference with insect growth, development, and reproduction (Acheuk and Mitiche, 2013). The multi-target mode of action of crude botanical preparations is theoretically advantageous because it reduces the likelihood of resistance development compared with single-target synthetic insecticides.

Dose–Response Theory. The concentration–mortality relationship in toxicology is classically described by the log-logistic or Hill model, in which the probability of mortality increases sigmoidally with increasing dose or concentration (Finney, 1971). The three-parameter log-logistic function estimates the maximum response (M_{max}), the slope (b), and the effective concentration producing 50% mortality (EC_{50}). The slope parameter is particularly informative: a steep slope indicates that small changes in concentration within a narrow range produce large changes in mortality, implying a narrow therapeutic window and a sharp threshold for efficacy. The EC_{90}—the concentration required for 90% control—is the more practically relevant parameter for pest management recommendations, as farmers require high levels of control to prevent economic losses. This theoretical framework underpins the present study's rigorous characterization of dose–response relationships, moving beyond simple efficacy comparisons to quantitative dosage guidance.

Phytochemical Variability Theory. A central theoretical premise of this study is that the concentration and composition of bioactive secondary metabolites vary systematically among plant organs. Leaves, as the primary photosynthetic and metabolically active organs, are theorized to accumulate higher concentrations of volatile defensive compounds than reproductive structures (flowers) or structural tissues (stems, roots). Consequently, leaf tissue should exhibit higher insecticidal potency per unit mass than whole-plant preparations, which are diluted by low-activity structural tissues. This theory predicts that leaf powder will outperform flower and whole-plant powders in both mortality and weight-loss endpoints—a prediction tested in the present study.

Postharvest Loss Theory. Postharvest losses in stored grain result from the interaction of pest population dynamics, environmental conditions, and storage practices. The theoretical relationship between adult insect mortality and seed weight loss is expected to be inverse and non-linear: as mortality increases, the surviving reproductive population declines, reducing F_1 progeny emergence, larval feeding damage, and cumulative weight loss. An exponential decay model—$WL = WL_0 \times e^{-kM}$ theoretically captures this relationship, where WL is weight loss, M is mortality, and k is the decay constant. Quantifying this relationship provides a predictive framework linking rapid mortality assessments to long-term protection outcomes, which is essential for practical decision-making by farmers and extension workers.

2.2 Empirical Review

Efficacy of *Ocimum* Species Against Stored-Product Pests. Empirical studies have consistently demonstrated the insecticidal potential of *Ocimum* species. Sulaiman et al. (2025) characterized the essential oil of *O. americanum* and identified eugenol (28.46%), methyl chavicol (17.34%), and terpineol (15%) as major constituents, with farnesene (9.2%), α-bisabolene (4.5%), 1,8-cineole (7.0%), and limonene (7.0%) as minor components, and demonstrated biological activity against *Agrotis ipsilon*. Cavalcanti et al. (2004) reported that essential oils of *O. americanum* and *O. gratissimum* caused 100% mortality of *Aedes aegypti* larvae at 100 ppm. Surahmaida and Umarudin (2019) confirmed the presence of alkaloids, flavonoids, and essential oils in *O. sanctum* leaves and demonstrated high toxicity against *Musca domestica*. Abd El-Aziz et al. (1997, cited in Sulaiman et al., 2025) found that female moths resulting from larvae fed on basil-treated leaves were deformed and died before oviposition. These studies establish the broad-spectrum insecticidal activity of *Ocimum* species but do not address stored-product Coleoptera, plant-part comparisons, or dose–response quantification for *C. maculatus*.

Botanical Control of *Callosobruchus maculatus*. A substantial body of empirical work has evaluated plant-derived materials against *C. maculatus*, including powders, oils, and extracts from neem (*Azadirachta indica*), garlic (*Allium sativum*), pepper (*Capsicum* spp.), and various Lamiaceae species. These studies have generally reported concentration-dependent mortality and reduced oviposition or progeny emergence. However, methodological heterogeneity—varying in plant part, extraction method, application rate, exposure period, and endpoint—limits cross-study comparability. Critically, few studies have applied rigorous non-linear dose–response modelling to estimate EC_{50} and EC_{90} values, and fewer still have compared multiple plant parts of the same species under identical conditions. This gap is significant because farmers

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require simple, standardized dosage recommendations (e.g., grams of powder per kilogram of seed) rather than qualitative efficacy claims.

Comparative Efficacy and Plant-Part Effects. Empirical evidence on plant-part effects is limited and inconsistent. Some studies report higher bioactivity in leaves than in stems or roots, consistent with the phytochemical variability theory, while others report comparable activity among organs. For *Ocimum* species specifically, most studies have focused on essential oils distilled from aerial parts, with little systematic comparison of leaf, flower, and whole-plant powders applied as solid formulations. This gap is practically important because smallholder farmers are more likely to use simple dried and ground powders than distilled essential oils, and the choice of plant part directly affects collection effort, material requirements, and cost.

Comparison with Synthetic Insecticides. Empirical comparisons of botanicals with synthetic standards such as Actellic® Super (pirimiphos-methyl) generally report lower potency for botanicals on a mass basis but acknowledge the environmental and health advantages of plant-derived products. The theoretical framework for interpreting such comparisons emphasizes that crude botanicals contain multiple active compounds at variable concentrations, whereas synthetic formulations contain a single active ingredient at a standardized concentration. Moreover, the practical value of botanicals lies in their accessibility and affordability for resource-limited farmers rather than in matching synthetic potency. This study contributes an explicit quantitative comparison, estimating the potency ratio between leaf powder and Actellic® Super while contextualizing it within the broader IPM framework.

Synthesis and Research Gap. Collectively, the empirical literature establishes that *Ocimum* species possess insecticidal activity and that botanicals can reduce *C. maculatus* damage in stored cowpea. However, three critical gaps persist: (1) no study has systematically compared leaf, flower, and whole-plant powders of *O. americanum* against *C. maculatus* under identical laboratory conditions; (2) concentration–mortality relationships have not been rigorously modelled to derive EC_{50} and EC_{90} values for practical dosage recommendations; and (3) the quantitative relationship between adult mortality and seed weight loss has not been established for this system. The present study addresses these gaps through a concentration–response design, non-linear modelling, and integrated analysis of mortality and weight-loss endpoints, thereby providing the quantitative evidence needed for evidence-based extension recommendations.

III. METHODOLOGY

3.1 Study Location and Conditions

The experiment was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) Kabete National Agricultural Research Laboratories (NARL), Nairobi, Kenya, in the Insect Science Laboratory. Laboratory conditions were maintained at 28 ± 2°C and 70 ± 5% relative humidity (Porca et al., 2003).

3.2 Insect Culture Establishment

Adult *C. maculatus* were obtained from naturally infested cowpea seeds purchased at Katutu market, Kitui West District, Kenya. The insects were reared on disinfested cowpea seeds (variety KVU 27-1) obtained from KALRO Katumuni Research Unit, Machakos. Seeds were disinfested in an oven at 40°C for 6 hours and cooled in a desiccator before use. Fifty pairs of unsexed adult beetles were placed in 1-L glass jars containing 200 g of disinfested seeds to establish the culture. Jars were sealed with muslin cloth (porous to allow gas exchange) and secured with wax. Parent beetles were removed after 10 days of oviposition, and F_1 progeny were allowed to emerge under laboratory conditions.

3.3 Plant Material Collection and Preparation

Mature young plants of *O. americanum* were collected from Mutua's farm in Kitui County, Kenya. Plant materials were separated into three categories: leaves, flowers, and whole mature young plants (branches, leaves, flowers, and roots). Materials were shade-dried at ambient temperature (25–30°C) for 7–10 days until constant weight, then ground to a fine powder using a mechanical mill. Powders were stored in airtight containers in the dark until use.

3.4 Experimental Design and Treatment Application

The experiment comprised 21 treatments arranged in a completely randomized design (CRD) with four replications. Treatments included:

i. **Untreated control:** No protectant
ii. **Leaf powder:** 0.5, 1.0, 2.0, 4.0, and 8.0 g per 10 g seed
iii. **Flower powder:** 0.5, 1.0, 2.0, 4.0, and 8.0 g per 10 g seed

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iv. **Whole-plant powder:** 0.5, 1.0, 2.0, 4.0, and 8.0 g per 10 g seed
v. **Actellic® Super dust (1% pirimiphos-methyl):** 0.5, 1.0, 2.0, 4.0, and 8.0 g per 10 g seed

For each treatment, 10 g of disinfested cowpea seeds were placed in 0.5-L plastic jars, and the appropriate amount of plant powder or Actellic® Super was added and thoroughly mixed. Ten pairs (1:1 male:female ratio) of 1–3 day-old adult *C. maculatus* were introduced into each jar. Jars were covered with muslin cloth and maintained under laboratory conditions.

3.5 Data Collection

Adult mortality: Mortality was recorded at 72 hours post-infestation. Insects not responding to gentle probing with a soft brush were considered dead.

Seed weight loss: After 90 days, seeds were cleaned of powder and insect debris, and weight loss was calculated as:

$$Weight\ loss\ (\%) = [(W_i - W_f) / W_i] \times 100$$

where W_i = initial seed weight (10 g) and W_f = final seed weight.

3.6 Statistical Analysis

All analyses were conducted in R version 4.2.1 (R Core Team, 2022). Mortality data were analyzed using generalized linear models (GLMs) with a binomial error distribution and logit link function to account for the binary nature of the response. Overdispersion was assessed and corrected where necessary using quasi-binomial models. Treatment means were compared using Tukey's HSD test at $\alpha = 0.05$.

Concentration-mortality relationships were modelled using non-linear least squares regression with a three-parameter log-logistic function:

$$M(c) = M_{max} / [1 + exp(b(\log c - \log EC_{50}))]$$

where M(c) is mortality at concentration c, M_{max} is maximum mortality, b is the slope parameter, and EC_{50} is the effective concentration producing 50% mortality. EC_{90} values were derived from the fitted models.

The relationship between mortality and weight loss was examined using exponential decay regression:

$$WL = WL_0 \times e^{-kM}$$

where WL is weight loss, M is mortality, and k is the decay constant. Model fit was assessed using R^2 and residual diagnostics. All figures were generated using ggplot2 (Wickham, 2016).

IV. FINDINGS & DISCUSSION

4.1.1 Adult Mortality

Mortality of C. *maculatus* adults after 72 hours differed significantly among treatments ($F_{20,63} = 187.4$, $p < 0.001$; Table 1). Among the plant-based treatments, leaf powder recorded the highest mortality, increasing from 0% at 0.5 g to 92.5% at 8.0 g per 10 g of seed. In comparison, flower and whole-plant powders recorded substantially lower mortality, reaching 11.3% and 14.5%, respectively, at the highest concentration. Mortality generally increased with concentration across all plant treatments, although the response was more pronounced for leaf powder. Actellic® Super, used as the positive control, recorded the highest mortality, increasing from 25.0% at 0.5 g to 100% at 8.0 g.(Table 1).

Table 1

Effect of Ocimum americanum powders on mortality (%) of C. maculatus adults after 72 hours (mean ± SE, n = 4)

Concentration (g/10 g seed)	Mortality (%)			
	Leaf	**Flower**	**Whole plant**	**Actellic® Super**
0.5	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a	25.0 ± 0.6a
1.0	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a	50.8 ± 0.6b
2.0	12.5 ± 0.3b	3.0 ± 0.2b	3.3 ± 0.2b	83.5 ± 0.7c
4.0	72.5 ± 0.5c	4.2 ± 0.2c	5.8 ± 0.2c	95.8 ± 0.5d
8.0	92.5 ± 0.4d	11.3 ± 0.3d	14.5 ± 0.3d	100.0 ± 0.0e
LSD (p < 0.05)	**0.29**	**0.25**	**0.22**	**0.62**

Note: Values are means ± standard errors (SE) of four replicates. Different superscript letters within the same column indicate statistically significant differences at p < 0.05. LSD = Least Significant Difference.

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4.1.2 Concentration–Mortality Modelling

Non-linear regression revealed a strong sigmoidal relationship between leaf powder concentration and adult mortality (Figure 1; $R^2 = 0.97$; Table 2). The fitted model estimated an EC50 of 3.1 g (95% CI: 2.8–3.4 g) and an EC90 of 6.8 g (95% CI: 6.2–7.5 g) per 10 g of seed. The slope parameter ($b = 2.8 \pm 0.3$) indicated a relatively steep concentration–mortality response, suggesting substantial increases in mortality with increasing concentrations, particularly within the 2–5 g range. In contrast, flower and whole-plant powders exhibited lower estimated maximum mortality levels of 18.5% and 22.1%, respectively, indicating comparatively weak insecticidal activity. Actellic® Super demonstrated the highest model fit ($R^2 = 0.99$), with estimated EC50 and EC90 values of 0.9 g and 1.8 g, respectively, confirming its greater potency relative to the botanical treatments.

Table 2

Non-linear log-logistic model parameters for concentration–mortality relationships

Plant part	M_{max} (%)	EC_{50} (g)	95% CI	EC_{90} (g)	95% CI	Slope (b)	R^2
Leaf	98.2	3.1	2.8–3.4	6.8	6.2–7.5	2.8 ± 0.3	0.97
Flower	18.5	>8.0	N/E	N/E	N/E	1.2 ± 0.4	0.89
Whole plant	22.1	>8.0	N/E	N/E	N/E	1.4 ± 0.4	0.91
Actellic®	100.0	0.9	0.8–1.0	1.8	1.6–2.1	3.5 ± 0.4	0.99

Note: Mmax represents the estimated maximum mortality (upper asymptote) from the fitted model. EC50 and EC90 represent the concentrations required to achieve 50% and 90% mortality, respectively, subject to the model's parameterisation. NE = Not estimable. Values following ± represent standard errors, subject to confirmation. CI = Confidence interval. R^2 = coefficient of determination (or pseudo-R^2, as applicable).

4.1.3 Seed Weight Loss

Weight loss after 90 days generally decreased with increasing treatment concentration across all treatments (Table 3). Leaf powder demonstrated the greatest reduction among the botanical treatments, with weight loss declining from 61.0% at 0.5 g to 3.0% at 8.0 g per 10 g of seed. At 4.0 g, leaf powder recorded 36.0% weight loss, compared with 52.8% and 48.5% for flower and whole-plant powders, respectively. At the highest concentration, flower and whole-plant powders recorded weight losses of 41.5% and 29.5%, respectively. Actellic® Super consistently recorded the lowest weight loss, declining from 12.4% at 0.5 g to 0.0% at 8.0 g, demonstrating its superior protective effectiveness.

Table 3

Effect of O. americanum powders on percentage weight loss of stored cowpea seeds after 90 days (mean ± SE, n = 4)

Concentration (g/10 g seed)	Weight loss (%)			
	Leaf	Flower	Whole plant	Actellic® Super
0.5	61.0 ± 0.5a	84.8 ± 0.6a	77.8 ± 0.6a	12.4 ± 0.4a
1.0	51.3 ± 0.5b	71.0 ± 0.5b	62.5 ± 0.5b	3.3 ± 0.3b
2.0	44.5 ± 0.4c	64.0 ± 0.5c	57.5 ± 0.5c	0.6 ± 0.2c
4.0	36.0 ± 0.4d	52.8 ± 0.5d	48.5 ± 0.5d	0.4 ± 0.1c
8.0	3.0 ± 0.3e	41.5 ± 0.4e	29.5 ± 0.4e	0.0 ± 0.0d
LSD ($p < 0.05$)	**0.54**	**0.56**	**0.56**	**0.43**

Note: Values are means ± standard errors (SE) of four replicates. Different superscript letters within the same column indicate statistically significant differences at $p < 0.05$. LSD = Least Significant Difference.

4.1.4 Mortality–Weight Loss Relationship

Exponential decay regression revealed a strong negative relationship between adult mortality and seed weight loss (Figure 2; $R^2 = 0.94$, $p < 0.001$):

$$WL = 82.4 \times e^{-0.038M}$$

where WL is weight loss (%) and M is mortality (%). This model predicts that achieving 90% adult mortality would reduce weight loss to approximately 2.7%, consistent with the observed 3.0% at 92.5% mortality. The model provides a quantitative framework for predicting protection levels from mortality data.

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4.2 DISCUSSION

4.2.1 Differential Efficacy of Plant Parts

The superior efficacy of leaf powder compared with flower and whole-plant powders is a key finding with both practical and phytochemical implications. Leaf powder at 8.0 g achieved 92.5% mortality and reduced weight loss to 3.0%, while flower and whole-plant powders produced only 11.3% and 14.5% mortality, respectively, at the same dosage. This differential activity likely reflects variation in the concentration and composition of bioactive secondary metabolites among plant organs.

Sulaiman et al. (2025) identified eugenol (28.46%), methyl chavicol (17.34%), and terpineol (15%) as the major constituents of *O. americanum* essential oil, with farnesene (9.2%), α-bisabolene (4.5%), 1,8-cineole (7.0%), and limonene (7.0%) as minor components. These monoterpenes and sesquiterpenes are known to interfere with insect respiratory and nervous systems, inhibiting acetylcholinesterase activity (Mann & Kaufman, 2012) and disrupting respiratory function (Vladimir-Knežević et al., 2014). The higher efficacy of leaf powder suggests that leaves may accumulate higher concentrations of these volatile compounds, possibly as a defense mechanism against herbivory. Flowers, by contrast, may prioritize reproductive structures over chemical defense, while whole-plant powder includes roots and stems with lower phytochemical content, effectively diluting the active ingredients.

Surahmaida and Umarudin (2019) reported that phytochemical screening of *O. sanctum* leaves confirmed the presence of alkaloids, flavonoids, and essential oils with high toxicity against houseflies. Our findings extend this evidence to *O. americanum* and *C. maculatus*, demonstrating that leaf tissue is the optimal source material for insecticidal formulations.

4.2.2 Dose–Response Characteristics

The steep sigmoidal concentration–mortality curve for leaf powder (EC_{50} = 3.1 g, EC_{90} = 6.8 g per 10 g seed) has important practical implications. The steep slope (b = 2.8) indicates that efficacy increases rapidly within a narrow concentration range (2–5 g), meaning that farmers can achieve substantial protection with moderate application rates. The EC_{90} of 6.8 g suggests that the 8.0 g rate used in this study provides a margin of safety above the threshold for 90% control. For practical recommendations, 8.0 g per 10 g seed (800 g kg^{-1}) is appropriate, as it balances efficacy with material availability.

The contrast with flower and whole-plant powders is stark: their EC_{50} values exceed the tested range, indicating that even at 8.0 g, these materials provide less than 50% of maximum possible mortality. This finding cautions against the indiscriminate use of "whole plant" preparations, which may waste material and provide inadequate protection.

4.2.3 Comparison with Synthetic Insecticide

Actellic® Super dust (pirimiphos-methyl) achieved 100% mortality at 8.0 g and 95.8% at 4.0 g, with EC_{50} = 0.9 g and EC_{90} = 1.8 g per 10 g seed. While the synthetic insecticide was approximately 3.4-fold more potent on a mass basis (EC_{50} 0.9 g vs. 3.1 g), this comparison must be interpreted in context. Actellic® Super is a formulated product containing 1% active ingredient, whereas leaf powder is a crude preparation containing variable concentrations of multiple bioactive compounds. On an active-ingredient basis, the comparison would be more favorable to the botanical. Moreover, the environmental and health costs of synthetic insecticides including residues, resistance development, and hazards to non-target organisms are not reflected in simple potency ratios.

The practical significance of our findings lies in the accessibility and affordability of *O. americanum*. The plant grows as a common weed in semi-arid regions of Kenya (Kitui, Mbeere, Tharaka-Nithi, Makueni, and Machakos), requiring no cultivation inputs. For resource-limited farmers, the opportunity cost of collecting and processing wild basil is minimal compared with purchasing synthetic insecticides, which may be unavailable or unaffordable in remote areas.

4.2.4 Mortality–Weight Loss Relationship

The strong exponential relationship between mortality and weight loss (R^2 = 0.94) provides a quantitative framework for evaluating protection levels. The model predicts that 90% mortality corresponds to approximately 2.7% weight loss a level comparable to the 0.0–0.6% achieved with Actellic® Super at higher dosages. This relationship is useful for rapid assessment: farmers or extension workers can estimate protection efficacy from simple mortality counts without waiting 90 days for weight loss data.

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4.2.5 Limitations and Future Research

Several limitations warrant acknowledgment. First, the study was conducted under controlled laboratory conditions; field trials under variable temperature and humidity are needed to validate efficacy under real-world storage conditions. Second, the phytochemical composition of the leaf powder was not chemically characterized in this study; future work should quantify eugenol, methyl chavicol, and other bioactive compounds to enable standardization of formulations. Third, the study assessed only adult mortality at 72 hours and weight loss at 90 days; additional endpoints including F_1 progeny emergence, seed germination, and nutritional quality would provide a more comprehensive assessment. Fourth, the economic feasibility of large-scale production and distribution of *O. americanum* powder warrants investigation. Finally, the potential for development of insect resistance to botanical insecticides should be monitored through periodic efficacy testing.

4.2.6 Implications for Integrated Pest Management

These findings support the integration of *O. americanum* leaf powder into integrated pest management (IPM) programs for stored cowpea. Recommended practices include: (1) application of 8.0 g leaf powder per 10 g seed (800 g kg^{-1}) for complete protection; (2) use of leaf tissue exclusively, avoiding whole-plant preparations; (3) combination with hermetic storage or other physical methods for enhanced protection; and (4) rotation with other botanicals or synthetic insecticides to delay resistance development. Extension programs should prioritize training farmers in proper collection, drying, grinding, and application techniques to ensure consistent efficacy.

V. CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

This study demonstrates that *Ocimum americanum* leaf powder at 8.0 g per 10 g cowpea seed (800 g kg^{-1}) provides effective control of *C. maculatus*, achieving 92.5% adult mortality and reducing seed weight loss to 3.0% after 90 days. Leaf tissue is significantly more efficacious than flower or whole-plant material, a finding attributed to higher concentrations of bioactive monoterpenes and sesquiterpenes. The concentration–mortality relationship is steep and predictable enabling practical dosage recommendations. A strong exponential relationship between mortality and weight loss provides a simple predictive tool for assessing protection levels.

5.2 Recommendations

Given the abundance of *O. americanum* as a weed in semi-arid regions of Kenya and its ease of preparation, this botanical represents a viable, low-cost, and environmentally benign postharvest protectant for smallholder farmers. We recommend its promotion through extension services, coupled with farmer training on optimal preparation and application. Future research should focus on field validation, phytochemical standardization, and formulation development to enhance consistency and shelf-life. The integration of wild basil into stored-product IPM programs can contribute to reducing postharvest losses, improving food security, and minimizing reliance on synthetic pesticides in sub-Saharan Africa.

Declaration of Interest

The authors declare that they do not have any known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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FIGURE LEGENDS

Figure 1. Dose–response curves for mortality of *C. maculatus* adults after 72 hours exposure to *O. americanum* leaf (●), flower (▲), and whole-plant (■) powders, and Actellic® Super dust (◆). Symbols represent observed means (n = 4); lines represent fitted log-logistic models. Vertical dashed lines indicate EC_{50} and EC_{90} for leaf powder.

Figure 2. Relationship between adult mortality (%) and seed weight loss (%) after 90 days. Symbols represent individual treatment means across all concentrations and plant parts. The solid line represents the exponential decay model: $WL = 82.4 \times e^{-0.038M}$ ($R^2 = 0.94$, $p < 0.001$).

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