


*Journal of Biological Control,* 39(3): 346–355, 2025, DOI: 10.18311/jbc/2025/49976

**Research Article**

# Repellent, attractant, and oviposition-deterrent effects of nano-encapsulated ginger, *Zingiber officinale* and cinnamon, *Cinnamomum zeylanicum* extracts on the southern cowpea weevil, *Callosobruchus maculatus* (F.)

**SARAH A. ABDULAMEER* and RAGHAD K. I. AL-JOBOORY**
*Department of Biology, College of Education, University of AL-Iraqia, Baghdad - 10001, Iraq*
**Corresponding author E-mail:* sara.a.abdulameer@aliraqia.edu.iq

**ABSTRACT:** This study aimed to evaluate the effects of chitosan-based nano capsules loaded with ginger, *Zingiber officinale* and cinnamon, *Cinnamomum zeylanicum* extracts on the southern cowpea weevil, *Callosobruchus maculatus*. Nanocapsules were prepared via the Ion gelation method and characterised by Scanning Electron Microscopy (SEM) and zeta potential analysis. The results demonstrated the successful fabrication of ginger extract-loaded nanocapsules with an average diameter of 172 nm and cinnamon extract-loaded nanocapsules with an average diameter of 192.75 nm. Additionally, the nanocapsules exhibited good colloidal stability, as indicated by a zeta potential of +30.45 mV. Repellent efficacy tests revealed that cinnamon extract nanocapsules achieved the highest repellency rate (56.7%), followed by ginger extract nanocapsules (36.7%). In comparison, conventional cinnamon and ginger extracts exhibited repellency rates of 43.3% and 26.7%, respectively. Oviposition inhibition assays further demonstrated the superiority of nanocapsules; ginger extract nanocapsules completely prevented egg laying (100%), whereas cinnamon extract nanocapsules inhibited oviposition by 26%. Conventional extracts of cinnamon and ginger inhibited egg laying by 59.1% and 46.7%, respectively. These findings indicate that both nano-formulations and conventional extracts of ginger and cinnamon possess repellent and oviposition-inhibiting activities against the southern cowpea weevil, *C. maculatus*, with nano-capsules showing enhanced efficacy. Therefore, nano-capsule formulations represent promising eco-friendly tools for mitigating pest damage and reducing weevil populations within Integrated Pest Management (IPM) programs. Also, further studies are needed to assess the long-term stability of nanocapsules and their effects on non-target organisms.

**KEYWORDS:** *Callosobruchus maculatus,* cinnamon, ginger, nanocapsules, oviposition deterrent

(Article chronicle: Received: 27-05-2025; Revised:18-09-2025; Accepted: 22-09-2025)

## INTRODUCTION

The southern cowpea weevil, *Callosobruchus maculatus* (F.) (Coleoptera: Chrysomeloidea), is one of the most economically significant pests affecting pulse crops (Gad *et al.*, 2021). This species infests both field and stored legumes, causing substantial quantitative and qualitative losses—including seed perforation, reduced weight and germination capacity, and overall deterioration of seed quality (Kalpna & Kumar, 2022).

As a major storage pest, *C. maculatus* inflicts heavy economic damage through direct destruction of agricultural produce (Hajam & Kumar, 2022). Recent research indicates that effective control of this weevil requires an integrated approach combining chemical and biological methods with advanced storage techniques to limit its spread (Kalpna, *et al*., 2022).

A variety of control strategies have been employed physical, biological, mechanical, and chemical. Although chemical treatments tend to be the most consistent, their environmental drawbacks and potential risks to consumers and non-target organisms are considerable. Biological control, for example, using the parasitoid *Anisopteromalus calandrae* to target weevil larvae, has shown promise (Ekeh *et al.*, 2020). Controlled-atmosphere treatments—reducing oxygen to 5% or elevating carbon dioxide can eliminate all life stages of the pest within 72 h (Hajam & Kumar, 2022). Resistant cultivars, such as IT99K-573-1, which is rich in tannins that inhibit larval development, have also been deployed (Omoike *et al.*, 2021).

Recent studies have highlighted the potential of botanical extracts in pest managementsuch as essential oils as bio-insecticide against the pulse beetle *Callosobruchus maculatus* (F.) (Mssillou *et al*,2022). For instance, alkaloid extracts from *Moringa oleifera* leaves have been shown to significantly suppress the growth, fertility, and population dynamics

of *C. maculatus* (Jassim *et al.*, 2024; Jasem *et al.*, 2024). Parallel research on nanoformulations has demonstrated that castor oil nanoemulsions enhance toxicity against mosquito larvae *Culex quinquefasciatus* while maintaining non-target organism safety (Al Hilfy *et al.*, 2022a, 2022b), underscoring the potential of nanotechnology to amplify the efficacy of biopesticides. Moreover, bionanocomposites have emerged as promising tools in integrated pest management. Silver nanoparticles synthesised using *Pseudomonas fluorescens* and *Bacillus thuringiensis* subsp. *tenebrionis* have exhibited remarkable efficacy in controlling both eggs and adults of C. maculatus (Ali *et al.*, 2024). Similarly, nanoencapsulated *Metarhizium anisopliae* extracts have demonstrated the ability to inhibit acetylcholinesterase activity in *Musca domestica* larvae, revealing the role of nanotechnology in enhancing the biochemical mechanisms of biopesticides (Hammed *et al.*,2022a, 2024b). In the context of social insect control, bionanoparticles derived from *Pseudomonas fluorescens* have been shown to disrupt cellulase enzyme activity in the digestive systems of termites, *Microcerotermes diversus,* thereby impairing their cellulose digestion capacity (Kamel *et al.*, 2022; Kamil *et al.*, 2023). Despite the environmental advantages of traditional plant extracts such as ginger and cinnamon, they face significant challenges, including rapid degradation due to environmental factors, poor solubility, and quick evaporation, which limit their practical effectiveness. This is where nanotechnology demonstrates its importance by offering innovative solutions through enhancing the stability of active compounds, protecting them from degradation, extending their lifespan, improving absorption, and providing controlled and targeted release that increases efficiency while reducing application frequency. Furthermore, chitosan nanoparticles enable the combination of multiple compounds to achieve a stronger synergistic effect, opening new horizons for developing highly effective botanical pesticides that can be applied on a large scale. This represents a qualitative leap in the field of biological pest control (Popletaeva and Arslanova ,2021).

Building on this evidence, there is a clear need to develop nanoformulations of plant extracts such as ginger, *Z. officinale* and cinnamon, *C. zeylanicum,* to enhance their pest control properties. This study evaluates chitosan-based nanocapsules loaded with ginger and cinnamon extracts, focusing on their repellent and oviposition-deterrent effects against *C. maculatus*. By bridging the gap between botanical biopesticides and nanotechnology, this research contributes to the advancement of eco-friendly pest management strategies within IPM programs.

Eco-friendly approaches, particularly botanical extracts, offer safe, cost-effective alternatives to synthetic pesticides. Cinnamon and ginger extracts are rich in secondary metabolites with insecticidal properties and exhibit high safety profiles for humans and non-target species, in addition to being inexpensive and easy to produce. However, when applied under field conditions, these extracts may degrade rapidly due to environmental factors, reducing their efficacy. Thus, there is a need for formulations that enhance stability and bioactivity. Nanotechnology provides such a solution: nanoparticles possess unique attributes—reduced size, increased surface area, and enhanced loading capacity that improve delivery and persistence of active compounds. In light of rising insect resistance to conventional pesticides and growing environmental concerns, nanoformulations of plant-derived biopesticides like cinnamon and ginger emerge as innovative tools. They enable lower application rates, greater stability, and targeted release of active ingredients, making them promising components of integrated pest management programs (Kah & Hofmann, 2013).

This study presents an innovative approach to pest control using ginger and cinnamon extracts, revealing a synergistic effect between their active compounds, such as gingerol and cinnamaldehyde, which enhances pesticidal efficacy while reducing required doses. The research stands out by focusing on molecular mechanisms of action and their impact on pest biological processes, such as disrupting the nervous system and chitin formation, while maintaining environmental and human safety through the use of readily available and low-cost natural materials. The findings provide a scientific basis for developing sustainable botanical pesticides applicable in integrated pest management systems, with potential for scaling up to protect crops and stored grains, thereby opening new horizons for natural alternatives to conventional chemical pesticides.

## MATERIALS AND METHODS

### Laboratory culture of southern cowpea weevil

The laboratory colony of the southern cowpea weevil, *Callosobruchus maculatus,* was established by collecting red cowpea seeds infested with this beetle from local markets in the Adhamiya district. Specimens were taxonomically confirmed at the Natural History Museum. Infested seeds were placed in ventilated plastic containers covered with muslin cloth and secured with rubber bands to prevent adult escape. Containers were maintained in an incubator at 25 ± 5°C and 70 ± 5% relative humidity (Al-Jabri & Mohammed, 1987). Cultures were monitored regularly to obtain sufficient numbers of adults for use in bioassays.

### Preparation of alcoholic extracts of ginger and cinnamon

Cinnamon bark and ginger rhizomes were obtained from local markets, thoroughly washed, and air-dried before being ground to a fine powder. For each extract, 50 g of powder

was macerated in 1000 mL of 99% ethanol. The mixtures were agitated periodically and stored in the dark for 48 h. After maceration, the suspensions were filtered through a Büchner funnel fitted with Whatman No. 1 filter paper and cheesecloth to remove coarse particles and impurities. The clear filtrates were then concentrated under reduced pressure at 45°C using a rotary evaporator to evaporate the solvent, yielding crude extract pastes. These pastes were collected in sterile vials and stored at 4°C until further use. The same procedure was applied to both ginger and cinnamon powders (Sasidharan *et al.*, 2019).

Aliquots of each crude extract were submitted for secondary-metabolite profiling by gas chromatography mass spectrometry (GC-MS) at the Scientific Research Authority's Centre for Environment and Water.

**Preparation of Chitosan nano-capsules loaded with ginger and cinnamon extracts**

Chitosan-based nano capsules incorporating crude ginger and cinnamon extracts were fabricated via the ionotropic gelation method Figure 1 (Salama *et al.*, 2022).

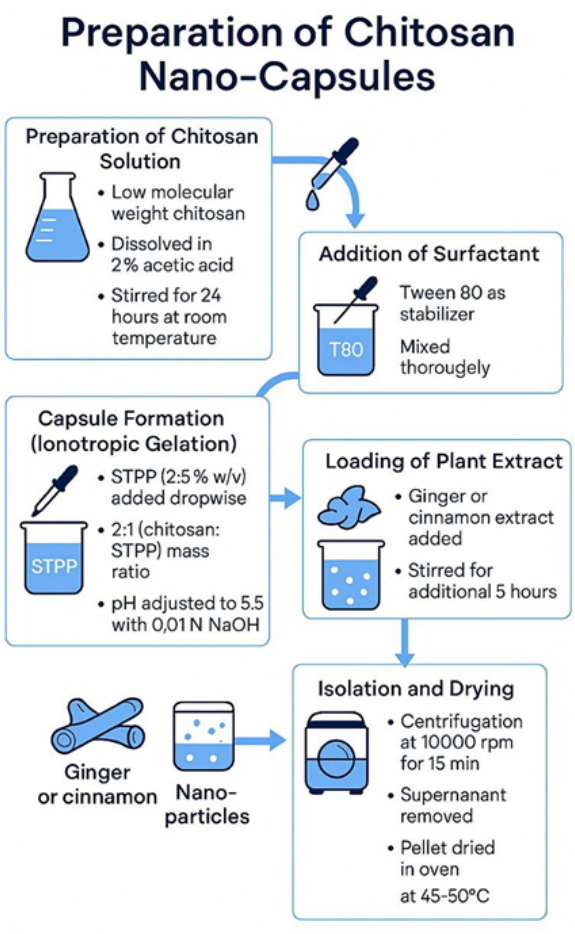



**Figure 1.** Preparation steps of nano-encapsulated cinnamon and ginger extract.

First, low molecular weight chitosan was dissolved in 2% (v/v) acetic acid and stirred at room temperature for 24 h to yield a clear solution. Tween 80 was then added as a stabilising surfactant and mixed thoroughly. A 2.5% (w/v) Sodium Tripolyphosphate (STPP) solution was introduced dropwise into the chitosan–Tween 80 solution at a chitosan: STPP mass ratio of 2:1 under continuous stirring. The pH of the mixture was adjusted to 5.5 using 0.01 N NaOH. Subsequently, the appropriate plant extract (either ginger or cinnamon) was added, and the suspension was stirred for an additional 5 h to ensure homogeneous nanoparticle formation. Nanoparticles were collected by centrifugation at 10,000 rpm for 15 min, after which the supernatant was discarded. The pellet was dried in an electric oven preheated to 45-50°C, ground to a fine powder, and stored in a dry, airtight container until required for bioassays (Salama *et al.*, 2022).

**Characterisation of the prepared nano-capsules**

The morphology and particle size of the chitosan nano-capsules were examined by SEM. Colloidal stability and surface charge were assessed through zeta potential analysis. All measurements were carried out at the Centre for Environment, Water, and Renewable Energies laboratories, Scientific Research Authority, Ministry of Higher Education.

**The repellent and attractant efficacy of conventional extracts and nanocapsules of ginger and cinnamon on adults of the southern cowpea beetle**

A chemotaxis apparatus was used to determine the repellent and attractant effects, consisting of three plastic tubes connected in an inverted T-shape. Each tube measured 30 cm in length. One end of the tube was sealed with a piece of cotton treated with the ginger nano-extract at the highest concentration of 0.75%. With three replicates, ten adult beetles were used. One end of the tube was treated with the extract, while the other end was sealed with cotton moistened only with water (control). Ten adult beetles were released from the central opening, and the apparatus was left in the dark for 3 hours. Afterwards, the number of adults moving toward the extract-treated end and those moving toward the control end was recorded.

The same procedure was repeated using the conventional extracts at the highest concentration of 2%, and similarly, the steps were repeated using the cinnamon extracts. The repellent and attractant effects were calculated according to the formulas of Shaaban and Nizar (1993).

- Repellency Percentage (%) = (Number of adults moving away from the treated side/Total number of insects) × 100
- Attractancy Percentage (%) = (Number of adults moving toward the treated side/Total number of insects) × 100

**Determination of the oviposition deterrent effect of conventional extracts and nanocapsules of ginger and cinnamon extracts**

The experiment was conducted using small plastic containers filled with healthy cowpea seeds, which were treated separately with ginger and cinnamon extracts at concentrations of 0.01% and 0.02% with 3 replicates for each treatment and using nanocapsules at concentrations of 0.5-0.75% with three replicates for each concentration. Two newly emerged adult beetles (one male and one female) were released into each replicate, with three replicates for each treatment. For the control treatment, seeds were treated with distilled water only. After 48 h, the number of eggs laid in both the treatment and control replicates was recorded. Based on these data, the oviposition deterrent effect was determined.

1. Oviposition Activity Index (OAI) was calculated according to the following formula:
   OAI = (NT-NC)/(NT+NC)

2. Egg Reduction Percentage (ER%) was calculated using the following formula:
   ER% = (NC-NT)/(NC)*100

Where:
- NC = Number of eggs laid in the control treatment
- NT = Number of eggs laid in the treated group (according to Danga *et al.*, 2018)

**Statistical analysis**

A Completely Randomised Design (CRD) was used, and treatment means were compared using the Least Significant Difference (LSD) test at a 5% probability level (Al-Sahookie & Wahib, 1990). The experimental data were analysed using the statistical software GENSTAT 12.

## RESULTS

**Identification of secondary metabolites in the ethanolic extracts of ginger and cinnamon using Gas Chromatography-Mass Spectrometry (GC-MS)**

The results presented in Table 1 show the secondary metabolites identified by GC-MS analysis in the ethanolic extract of ginger. Six compounds were detected, with Chloroacetic acid, 10-undecenyl ester being the most abundant at 72.15%, followed by Dimethylamine at 25.04%, and Ethylformanilide at 1.93%. Similarly, the results in Table 2 show the analysis of the secondary metabolites detected in cinnamon extract, arranged according to Retention Time (RT) values and their corresponding percentages. The most abundant compound was Dimethylamine at 47.38%, followed by Cinnamaldehyde at 31.49%, and 1-Ethynylcyclododecanol at 19.55%.

**Table 1.** Secondary metabolites identified by GC-MS analysis in the ethanolic extract of Z. *officinale*

| Peak no. | RT | Structure | Chemical name | % Area | % SI |
|---|---|---|---|---|---|
| 1 | 2.041 | $C_2H_7N$ | Dimethylamine | 25.04 | 96 |
| 2 | 13.938 | $C_3H_7NO_2$ | dl-Alanine | 0.63 | 92 |
| 3 | 18.211 | $C_9H_{11}NO$ | 2-Ethylformanilide | 1.93 | 100 |
| 4 | 20.076 | $C_{13}H_{23}ClO_2$ | Chloroacetic acid, 10-undecenyl ester | 72.15 | 76 |
| 5 | 20.221 | $C_5H_6N_2$ | Pentanedinitrile | 0.17 | 87 |
| 6 | 20.300 | $C_4H_8O_2$ | Butanoic acid | 0.08 | 77 |

**Table 2.** Secondary metabolites identified by GC-MS analysis in the ethanolic extract of *C. zeylanicum*

| Peak no. | RT | Structure | Chemical name | % Area | % SI |
|---|---|---|---|---|---|
| 1 | 2.042 | $C_2H_7N$ | Dimethylamine | 47.38 | 95 |
| 2 | 9.558 | $C_9H_8O$ | Cinnamaldehyde | 31.49 | 92 |
| 3 | 12.087 | $C_9H_60_2$ | Coumarin | 0.41 | 90 |
| 4 | 12.975 | $C_8H_7N_3O$ | 2-Pyridin-2-yl-5-methyl-1,3,4-oxadiazole | 0.00 | 100 |
| 5 | 13.938 | $C_9H_{10}O_2$ | Benzenamine, 2,3,4,5-tetramethyl | 0.38 | 95 |
| 6 | 18.223 | $C_6H_{16}Si$ | Silane, trimethylpropyl- | 0.43 | 78 |
| 7 | 20.093 | $C_{14}H_{24}O$ | 1-Ethynylcyclododecanol | 19.55 | 77 |

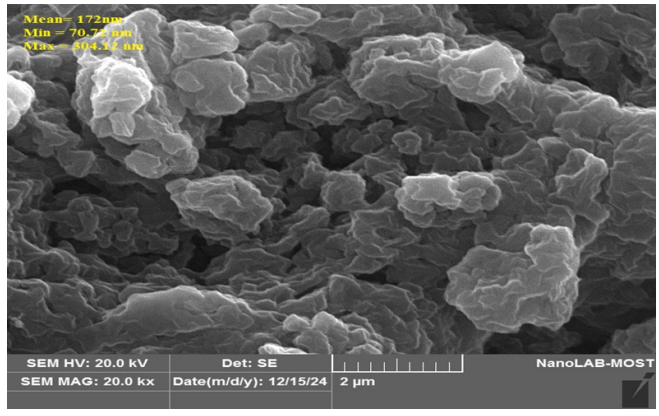



**Figure 2.** Scanning Electron Microscope image of the nanocapsules of ginger extract.

**Determination of some properties and specifications of the prepared nanocapsules**

The SEM images (Figure 2) showed the formation of irregular, quasi-spherical nanocapsules of ginger extract with a diameter of 172 nm. Similarly, the SEM images (Figure 3) showed the formation of irregular, quasi-spherical nanocapsules of cinnamon extract with a diameter of 192.75 nm. Furthermore, Figure 4 presents the zeta potential of the ginger extract nanocapsules, which recorded a value of

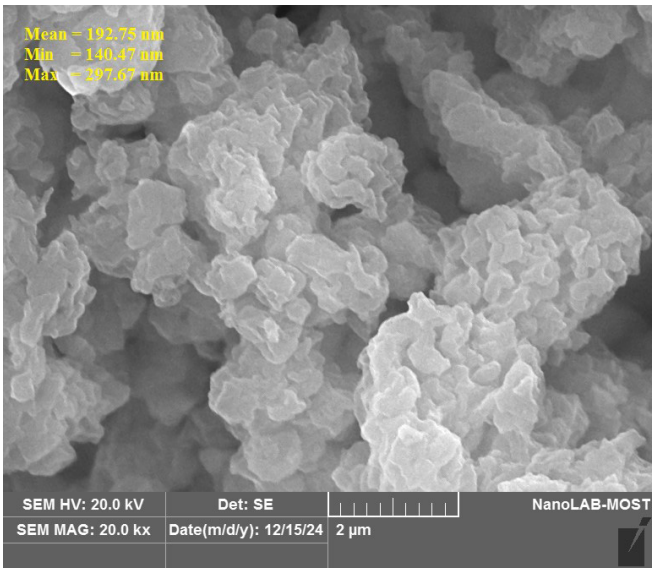



**Figure 3.** Scanning Electron Microscope image of the nanocapsules of ginger extract.

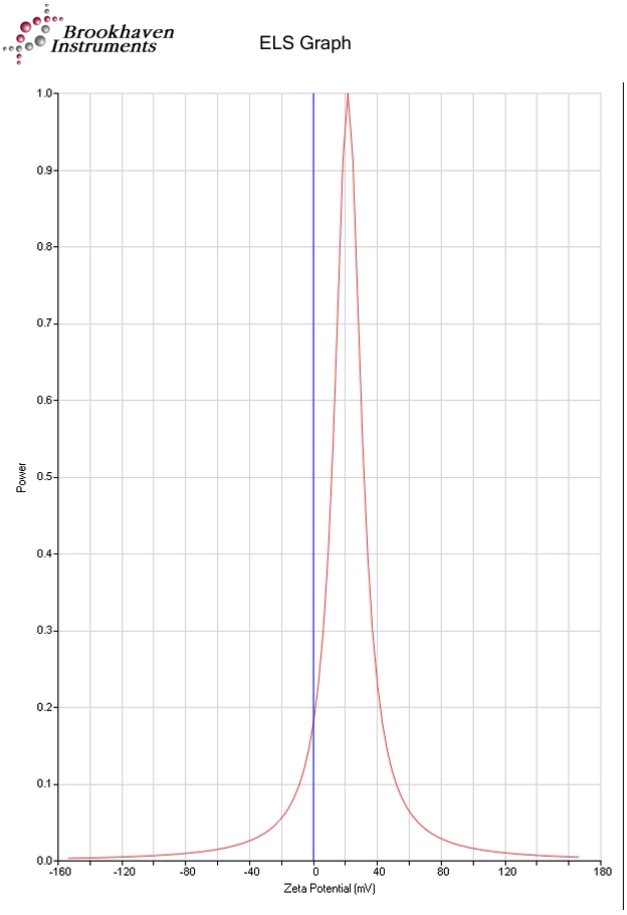



**Figure 4.** Zeta potential of the nanocapsules of ginger extract.

21.56 mV, indicating good stability of the nanocapsules and their resistance to aggregation. Likewise, the zeta potential of the cinnamon extract nanocapsules reached 30.45 mV, also indicating good stability of the nanocapsules (Figure 5).

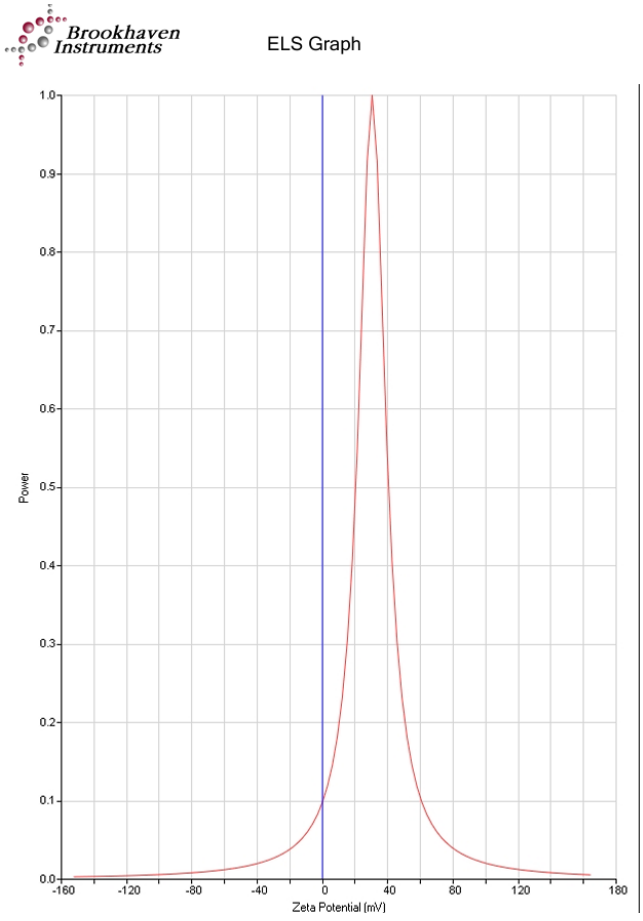



**Figure 5.** Zeta potential of the nanocapsules of cinnamon extract.

### Repellent and attractant effects of ginger and cinnamon extracts on adults of the southern cowpea beetle

The results presented in Figure 6 demonstrate the effect of the optimal concentrations of both the extracts and nanocapsules of cinnamon and ginger on the repellent and attractant rates for the adult beetles. The repellent percentages for the cinnamon extract, cinnamon nanocapsules, ginger extract, and ginger nanocapsules were 6.7%, 20%, and 20%, respectively. It is observed that the highest attractant percentage was 20%, while the lowest was 6.7%. Statistical analysis results showed no significant differences in the attraction percentage when treated with cinnamon nanocapsules, ginger nanocapsules, and ginger extract. These treatments, however, differed significantly from the cinnamon extract treatment. As shown in Figure 7, the repellent percentages for the aforementioned treatments were 36.7%, 26.7%, 56.7%, and 43.3%, respectively. It is observed that the highest repellent percentage was 56.7%, and the lowest was 26.7%. The results indicated significant differences between all nanocapsule and non-nanocapsule treatments, with cinnamon nanocapsules exhibiting the highest repellent effect.

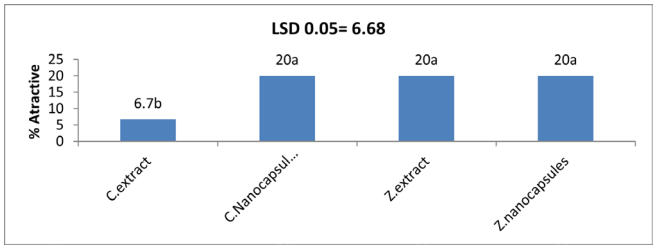



**Figure 6.** Attraction percentages of southern cowpea beetle adults when treated with nanocapsule and conventional extracts of ginger and cinnamon.

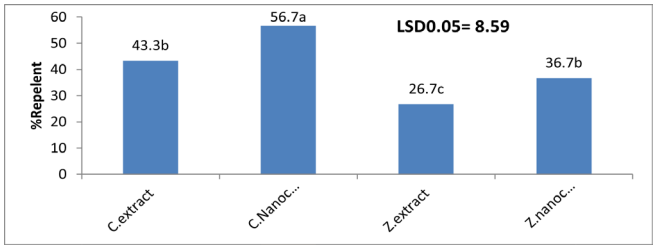



**Figure 7.** Repellent percentages of southern cowpea beetle adults when treated with nanocapsule and conventional extracts of ginger and cinnamon.

## Oviposition deterrence of southern cowpea beetle when treated with nanocapsules and conventional extracts of ginger and cinnamon

The results presented in Table 3 indicate that treatment with different concentrations of alcoholic extracts of both cinnamon and ginger leads to inhibition of egg laying. This is evident from the values of the Oviposition Activity Index in the table, where negative values indicate inhibition of egg laying, while positive values indicate no inhibition. Statistical analysis results showed no significant differences between the two types of extracts in terms of inducing the inhibition process. Additionally, the statistical analysis revealed no significant differences between the concentrations and their effect on the inhibition process. The interaction between the studied factors did not affect the Oviposition Activity Index.

The results shown in Table 4 display the egg-laying inhibition percentages when treated with different concentrations of cinnamon and ginger extracts. The results showed that the inhibition percentage when treated with a 1% concentration of cinnamon alcoholic extract was 58.4%, whereas at a 2% concentration, it decreased to 6.3%. It is also noted that the inhibition percentage when using ginger extract was 46.7%, while it decreased to 42% at a 2% concentration. Statistical analysis results revealed significant differences in the egg-laying inhibition percentages, with a notable superiority of the ginger alcoholic extract. Furthermore, the statistical analysis indicated significant differences between the concentrations, with a preference for the 1% concentration, showing a significant difference. The results also suggest that

**Table 3.** Oviposition activity index of the southern cowpea beetle when treated with conventional extracts of ginger and cinnamon

| Type of extract | Concentration (%) | OAI | Mean |
|---|---|---|---|
| C. crude ext. | 1 | -0.48 | -0.21 |
| | 2 | -0.07 | |
| Z. crude ext. | 1 | -0.27 | -0.31 |
| | 2 | -0.36 | |
| Conc. mean | 1a | 2 b | |
| | -0.37 | -0.14 | |
| LSD 0.05 | Type of extract = 0.57 Conc.= 0.57 Type of ext. × Conc=0.8$^{NS}$ | | |

**Table 4.** Egg-laying inhibition percentage of the southern cowpea beetle when treated with conventional extracts of ginger and cinnamon

| Type of extract | Concentration (%) | %ER | Mean |
|---|---|---|---|
| C. crude ext. | 1 | 58.4 | 32.4 b |
| | 2 | 6.3 | |
| Z. crude ext. | 1 | 46.7 | 44.3 a |
| | 2 | 42.0 | |
| Conc. mean | 1a | 2b | |
| | 52.5 | 24.1 | |
| LSD 0.05 | Type of extract = 5.7 Conc.= 5.6 Type of ext. × Conc = 7.9* | | |

the interaction between the studied factors had a significant impact on the egg laying inhibition percentages due to the presence of secondary compounds (Bouguerra *et al.*, 2017).

## Egg laying inhibition by nanocapsules of ginger and cinnamon extracts

The results presented in Table 5 show that treatment with different concentrations of nanocapsule extracts of both cinnamon and ginger leads to inhibition of egg laying. This is evident from the egg-laying index values in the table, where negative values indicate inhibition of egg laying, while positive values indicate no inhibition. Statistical analysis results revealed no significant differences between the two types of extracts in terms of inducing the inhibition process. Additionally, the statistical analysis indicated no significant differences between the concentrations and their effects on inducing the inhibition process. The interaction between the studied factors did not affect the egg laying index.

The results shown in Table 6 display the egg laying inhibition percentages when treated with different concentrations of the nanocapsule extracts of cinnamon and ginger. The results showed that the inhibition percentage when treated with a 0.5% concentration of cinnamon nanocapsule extract was 0.0%, while at a 0.75% concentration, it increased to 26.7%. It is also noted that the inhibition percentage when

**Table 5.** Egg laying index of southern cowpea beetle when treated with nanocapsule extracts of ginger and cinnamon

| Type of extract | Concentration (%) | OAI | Mean |
|---|---|---|---|
| C. nanocapsules | 0.5 | 0.33 | 0.09 |
| | 0.75 | -0.14 | |
| Z. nanocapsules | 0.5 | 0.02 | 0.49- |
| | 0.75 | -1.00 | |
| Conc. mean | 0.5 | 0.75 | |
| | 0.18 | -0.75 | |
| LSD 0.05 | Type of extract = 0.48 Conc. = 0.47 Type of ext. *conc= 0.67 | | |

**Table 6.** Egg-laying inhibition percentage of the southern cowpea beetle when treated with nanocapsule extracts of ginger and cinnamon

| Type of extract | Concentration (%) | % ER | Mean |
|---|---|---|---|
| C. nanocapsules | 0.5 | 0.0 | 13.3 b |
| | 0.75 | 26.7 | |
| Z. nanocapsules | 0.5 | 25.1 | 62.5 a |
| | 0.75 | 100.0 | |
| Conc. mean | 0.5 | 0.75 | |
| | 12.5 b | 63.3 a | |
| LSD 0.05 | Type of extract = 15.1 Conc. = 15.1 Type of ext. *conc = 21.35 | | |

using ginger nanocapsule extract was 25.1%, and it reached 100% at the 0.75% concentration. Statistical analysis results revealed significant differences in egg laying inhibition percentages, with a notable superiority of the ginger nanocapsule extract. Furthermore, the statistical analysis indicated significant differences between the concentrations, with a preference for the 0.75% concentration.

As shown in Figure 8, a comparison was made between the best concentrations of nanocapsule and conventional extracts of cinnamon and ginger and their effect on egg laying inhibition percentages. The best egg-laying inhibition was observed with ginger nanocapsules, which achieved 100%, while the lowest inhibition percentage was observed with cinnamon nanocapsules, which reached 26.7%. Statistical analysis results revealed significant differences in egg laying inhibition percentages between the nanocapsule and conventional preparations, with a significant preference for ginger nanocapsules over the other preparations.

## DISCUSSION

Plant-derived compounds such as cinnamaldehyde and gingerol - identifiable through GC-MS analysis - demonstrate significant efficacy in insect control. Cinnamaldehyde acts as both an insect repellent and

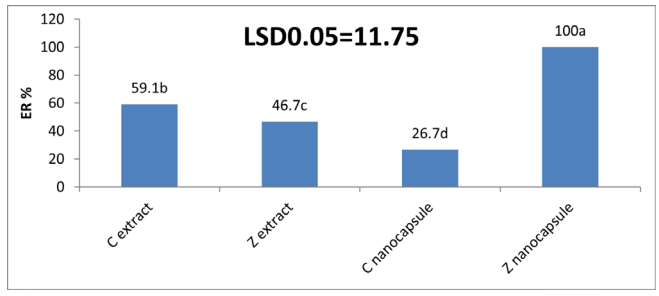



**Figure 8.** Comparison of egg laying inhibition effect at the best nanocapsule and conventional treatments of cinnamon and ginger extracts.

insecticide by targeting the nervous system through GABA receptors and inhibiting larval respiration, making it an effective component in organic pesticides and mosquito nets. Gingerol exhibits mosquito-repellent properties and egg-laying inhibition by interfering with insects' chemosensory system, positioning it as a promising natural alternative for insect repellent formulations. Other bioactive compounds like eugenol and limonene show similar insecticidal properties. However, these compounds face challenges, including the need for high concentrations and lower environmental stability compared to synthetic pesticides, highlighting the need for further research to enhance their effectiveness and cost-efficiency as eco-friendly pest control solutions. (Rattan *et al.* 2016; Ong *et al.*, 2020).

Previous studies have shown that cinnamaldehyde effectively inhibits neural enzymes related to insect locomotion (Eesiah, 2021). The repellent effect of plant compounds is believed to stem from their interaction with olfactory receptors, causing insects to avoid treated materials. This repellency can significantly reduce stored seed infestation by preventing insect feeding (Kadir *et al.*, 2025). Nanocapsules demonstrate superior performance compared to conventional extracts due to their unique properties: Smaller size, enhancing penetration and efficacy. Controlled release of active compounds, ensuring prolonged availability. Increased degradation efficiency of target materials (Kadir *et al.*, 2025). Additionally, the interaction between studied factors significantly influenced egg-laying inhibition percentages, likely due to secondary bioactive compounds (Bouguerra *et al.*, 2017).

Ginger nanocapsules showed particularly strong inhibition of egg-laying enzymes. This enhanced effect can be attributed to: Greater surface area of nanoparticles, improving ginger's bioactive availability. Efficient cellular penetration, surpassing conventional formulations. High phenolic content (*e.g.*, gingerol) effectively disrupts biological processes in target insects (Ghormade *et al.*, 2011). In contrast, cinnamon components (*e.g.*, cinnamaldehyde) may act through different

mechanisms, resulting in weaker egg-laying suppression. Comparative studies indicate that while cinnamon provides faster repellency, ginger offers delayed but more sustained insecticidal effects (Adetuyi *et al.*, 2024). Numerous studies demonstrate that chitosan nanocapsules significantly enhance the stability, bioavailability, and sustained release of plant bioactives. For ginger, gingerol-loaded chitosan nanoparticles show increased uptake and longevity of activity (El-Derbawy *et al.*, 2022). Chitosan's small size and mucoadhesive properties improve penetration to insect targets, amplifying effectiveness through mechanical delivery mechanisms. While cinnamaldehyde can also be encapsulated effectively with improved release profiles, its single-compound nature lacks the broader biochemical targets seen in ginger's diverse phytochemical profile, which explains why ginger nanocapsules often outperform cinnamon in inhibiting oviposition ( Sarjono *et al.*, 2018).

## CONCLUSION

Results indicated that ginger and cinnamon extracts contain secondary metabolites with insect-repellent properties and can be formulated into chitosan-based nano-capsules. These nano-capsules, characterised by their small size and high stability, exhibited superior repellent and oviposition-inhibiting efficacy against the southern cowpea weevil, *Callosobruchus maculatus* compared to conventional extracts. This enhanced performance is attributed to their nanoscale dimensions, which allow for lower effective concentrations, as well as their ability to protect active compounds from degradation and to release them gradually. Unlike rapidly degrading conventional extracts, the nano-capsules provide sustained release, prolonged efficacy, and stability under diverse environmental conditions. Therefore, these are recommended as an eco-friendly solution for pest management, particularly within IPM programs, under storage conditions.

## ACKNOWLEDGEMENTS

The work has been undertaken as part of the master's degree research programme and a demand-driven project at the Department of Biology, Education College, Al-Iraqia University, Iraq. The first author is extremely thankful for providing scientific and laboratory facilities provided for conducting the work.

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