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Research Article

Insecticidal properties of nanoencapsulated essential oil of *Cuminum cyminum* on *Sitophilus oryzae* and *Tribolium castaneum*

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Abstract: The rice weevil, *Sitophilus oryzae* L., and the red flour beetle, *Tribolium castaneum* (Herbst), are major storage pests with a global distribution, causing significant damage to agricultural products. Increasing attention has been directed toward the use of plant essential oils as natural and eco-friendly alternatives. However, their low water solubility, high susceptibility to oxidation, and instability limit their direct application. In this regard, advanced formulation technologies offer an effective approach to enhance the stability and efficacy of essential oils for pest control. In the present study, the essential oil of *Cuminum cyminum* L. was encapsulated by *in situ* polymerization of an oil/water (O/W) emulsion at the nanoscale. The contact toxicity and repellent activity of the essential oil were evaluated against *S. oryzae* and *T. castaneum* before and after formulation. All experiments were conducted with four replications, including a control treatment, under controlled conditions at 25 ± 1 °C, 65 ± 5% relative humidity, and in the dark. The results indicated that in contact toxicity assays using the spraying method, the nanoformulation demonstrated superior efficacy. Moreover, repellent activity assays revealed that while the pure essential oil showed stronger short-term repellency (up to 6 hours post-exposure), the formulated oil exhibited significantly higher repellency after 24 hours. Overall, nanoencapsulation improved the contact toxicity and prolonged repellency compared with the pure essential oil against stored-product pests. Therefore, these results highlight the promising potential of plant-based nanoformulations for sustainable pest management.

Keywords: Essential oil, Contact toxicity, nanoencapsulation, *Sitophilus oryzae*, *Tribolium castaneum*

Introduction

Over the last decades, essential oils derived from medicinal plants have attracted interest because of their toxicity to pests. Plant compounds have attracted interest because of their contact and respiratory toxicity, repellency, environmental compatibility, biodegradability, shorter half-lives, low toxicity to mammals, low environmental persistence, and slower development of insect resistance (Lowry *et al*., 2019; Isman, 2020; Farina and Conti, 2024).

The major components of essential oils are monoterpenes, phenols, and sesquiterpenes,

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which have been shown to be effective against a variety of pests (Wilson and Isman, 2006; Abdelgaleil *et al*., 2024). In addition to their insecticidal action, plant essential oils may also display antifungal, antitumor, and antimicrobial properties (Sacchetti *et al*., 2005; Wang *et al*., 2006). Although essential oils in pest control offer numerous benefits, their use also has several limitations.

The volatility, low solubility in water, quick oxidation, and chemical instability of plant essential oils, which are sensitive to air, light, moisture, and high temperature (Pillmoor *et al.,*1993; Turek and Stintzing, 2013), have prompted the search for new methods to improve the toxicity and effectiveness of essential oils before application in pest management.

One crucial strategy is designing novel formulations and modifications that enhance the quality and activity of essential oils. Nanotechnology is an emerging field that is increasingly important in modern technology. Over the past decade, it has shown the potential to transform agricultural practices (Moharramipour and Negahban, 2014; Nuruzzaman *et al*., 2016).

The choice of formulation depends on the physical, chemical, and biological characteristics of the essential oil, mechanism of action, method of application, and type of product. To enhance efficacy and minimize environmental hazards, controlled-release formulations appear most suitable (Maji *et al*., 2007; Negahban *et al*., 2007). Thus, nano- and microencapsulation of essential oils imparts controlled-release properties, which can enhance and prolong their biological activity (Lai *et al*., 2006; Aghazadeh *et al*., 2025).

The rice weevil, *Sitophilus oryzae* L. (Coleoptera: Curculionidae), and the red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), are some of the most devastating global pests and cause large economic losses of stored products. *S. oryzae* has been reported as one of the most severe pests of cereal grains and their products (Baloch, 1992; Lee *et al*., 2001). *T. castaneum* is a cosmopolitan and serious pest of cereal grains and their products. Adult beetles and larvae feed on stored foodstuffs, including dry fruits, pulses, bran, coat, germ, grain dust, and prepared cereal foods (Atwal, 1976; Hamed and Khattak, 1985; Khattak *et al*., 1999; Dars *et al*., 2001; Brown *et al*., 2009; Campbell *et al*., 2022).

Given these insects' strong resistance to most pesticides and the high effectiveness of essential oils in managing stored-product pests, this study evaluated *C. cyminum* essential oil and its nanoencapsulated formulation for managing stored-product infestations. Therefore, the objective of this study was to evaluate the contact toxicity and repellent potential of *C. cyminum* essential oil and its nanoencapsulated formulation against *S. oryzae* and *T. castaneum* under identical laboratory conditions. We hypothesized that nanoencapsulation would improve contact toxicity and repellency compared with the pure oil. Unlike Negahban *et al*. (2012b), who focused on the fumigant toxicity of nanoencapsulated *C. cyminum* against *T. castaneum*, this study directly compares pure and formulated oil against two major stored-product pests and characterizes the temporal pattern of repellency over 24 h.

Materials and Methods

Insect culture

Adult *S. oryzae* were collected from infested rice grains and wheat groats, and adult *T. castaneum* were collected from infested flour in the rearing building of the Entomology Department in the Faculty of Agriculture at Tarbiat Modares University. Following species identification, a mass rearing program for the insects was started. Adult *S. oryzae* and *T. castaneum* were utilized in the experiments. *S. oryzae* were fed on Hashemi rice grains, and *T. castaneum* were fed 95% wheat flour + 5% yeast. The insects were maintained at 25 ± 1 °C and 65 ± 5% relative humidity, in a germinator under complete darkness. Insects were maintained under the above conditions for at least 20 generations before the experiments. Adults aged 1–7 days were obtained by collecting newly emerged adults from synchronized cultures every 24 h. Sex was not controlled; mixed-sex populations

were used because mortality and repellency were assessed at the population level. For each replicate, insects were randomly allocated from the same synchronized cohort to treatment and control groups.

Formulation of nanoencapsulation

All formulation procedures were conducted at the Faculty of Agriculture, Tarbiat Modares University. Nanoencapsulation of *C. cyminum* essential oil was performed using the in-situ polymerization technique (addition–condensation polymerization) through an oil-in-water (O/W) emulsion system (Negahban *et al*., 2013a, b). The essential oil was employed as the core material of the nanocapsules, while urea and 37% aqueous formaldehyde were utilized for the synthesis of urea–formaldehyde (U–F) prepolymers, which served as the wall-forming matrix of the nanocapsules. To prepare the prepolymer, urea and formaldehyde solution were added to a reactor equipped with a homogenizer and allowed to react under controlled conditions.

Following the formation of the U–F prepolymer, the stirring rate was increased, and the emulsifier was gradually incorporated into the reaction medium. The essential oil was subsequently added dropwise to form a stable emulsion. Then, the pH was adjusted to acidic conditions to initiate polymerization and promote the deposition of poly(urea–formaldehyde) around the dispersed oil droplets. The reaction proceeded for 4 hours to ensure complete polymerization and stabilize the formed nanocapsules (Negahban et al., 2013a,b). The concentration of *C. cyminum* essential oil was determined proportionally to the total formulation components, such that the final nanoformulation contained 2% (w/w) active ingredient.

Contact toxicity of pure and nanocapsules containing the essential oil

To determine the concentration needed to achieve 50% mortality of the adult insect population (LC_{50}), preliminary experiments were conducted to identify concentrations resulting in 20%-80% mortality. Subsequently, the test concentrations were selected on a logarithmic scale, and the experiment was conducted as follows. To investigate the contact toxicity of the essential oil and essential oil-containing nanocapsules, we sprayed both the insects and the inner surfaces of the Petri dishes. Therefore, the observed mortality represents combined direct topical exposure and exposure to treated surfaces. It should not be interpreted as purely topical toxicity.

A spray device connected to a nitrogen cylinder available in the entomology laboratory of the Faculty of Agriculture was used for spraying. To achieve an even coating of the test material (liquid formulation) on a circular surface with a 9 cm diameter, the spray tower pressure was set to 5 pounds per square inch, and 1 milliliter was sprayed per application. Ten adult flour beetles and rice weevils were placed into Petri dishes. To improve ventilation, the center of the Petri dish lid was perforated with a 2 cm diameter hole and covered with mesh. At 24 hours after treatment, the number of dead insects in the treated containers and the control group was counted, and the percentage of mortality was calculated (Abbott, 1925). Concentrations of 8000, 10000, 12000, 14000, and 16000 ppm of *C. cyminum* essential oil were prepared and used for *T. castaneum*, and concentrations of 10000, 12000, 14000, 16000, and 18000 ppm were prepared and used for *S. oryzae.* For the formulation of *C. cyminum* essential oil, concentrations of 200, 400, 600, 800, and 1000 ppm were prepared and used for *T. castaneum*, and concentrations of 600, 800, 1000, 1200, and 1500 ppm were prepared and used for *S. oryzae*. All concentrations are expressed as essential-oil equivalents, and we compare the pure oil and the formulation on an equivalent active-ingredient basis.In the control container, 1 milliliter of 5% ethanol was sprayed. This experiment was carried out with 4 replications, including the control group, at temperature conditions of 25 ± 1 °C, relative humidity of 65 ± 5%, and total darkness. For further evaluation, the insects were transferred to clean containers, and their mortality status was

reevaluated after 24 hours. LC_{50} values for the test insects at concentrations inducing 20%-80% mortality were calculated using SPSS 18.

Repellency of pure essential oil and nanocapsules containing the essential oil

According to the procedure of Shakarami *et al.* (2003) with slight alterations, an opening was made on each side of a plastic jar (a cubic-shaped container with a lid of 65 milliliter capacity). Each of the holes was connected by a plastic tube 3 millimeters in diameter and 2 centimeters in length to two plastic containers of equal volume, in a way that the insects could move freely from the center container to the side containers via the connecting tubes. For this experiment, the control container received a 45-milligram rice disk (for the *S. oryzae*) and a 45-milligram flour disk (for the *T. castaneum*) (and one milliliter of acetone for the essential oil and one milliliter of water for the essential oil formulation). A milliliter of the different concentrations of nanocapsules of the essential oil or pure essential oil was added to the disks in the treatment container. For *C. cyminum* essential oil and nanocapsules of the essential oil, 3400, 3800, 4100, 4500, and 4800 ppm concentrations were used for *T. castaneum* and 2000, 2800, 3100, 3500, and 4000 ppm for *S. oryzae*. In the experiments, 10 adults *T. castaneum* and *S. oryzae* aged 1 to 7 days (after 3 hours of starvation) were released into the central container. During the experiment, the containers were left open but covered with mesh. After 1, 3, 6, 12, and 24 hours, the number of insects in each container was counted, and the repellency percentage (%) of the conventional essential oil and nanoencapsulated essential oil was calculated. The experiments were conducted in 4 replicates. The repellency percentage (%) of the conventional and nanoencapsulated essential oils was calculated using the following formula (Liu *et al*., 2006)

$$\text{Repellent Index (RI)}\% = \frac{C - T}{G} \times 100$$

- C = number of insects in the control container,
- T = number of insects in the treatment container,
- G = Total number of insects tested.

Insects remaining in the central chamber were not assigned to either the control or the treatment chamber. They were included only in G, the total number of insects tested. The repellency index therefore represents the net distribution between treated and control chambers relative to the total number of released insects.

To compare the effects of different concentrations within each treatment (essential oil or nanoencapsulated essential oil) on the repellency index, a one-way ANOVA was used. If the results were statistically significant, the means were further compared using Tukey's test at a 5% significance level. Before statistical analysis, the repellency index was normalized using the following transformation: $\text{Arcsine}\sqrt{\frac{x}{100}}$

Statistical analyses were performed using SPSS 18, and graphs were generated using Microsoft Excel 2007.

Results

Contact toxicity of pure and nanoencapsulated essential oil on adult insects

The results indicate that the LC_{50} values of pure *C. cyminum* essential oil against adult *S. oryzae* and *T. castaneum* after 24 hours of exposure were 11488 ppm and 9194 ppm, respectively.

In contrast, the LC_{50} values obtained from nanoencapsulated cumin essential oil under the same conditions were significantly lower: 810 ppm for *S. oryzae* and 297 ppm for *T. castaneum* (Table 1). The findings on the efficacy of *C. cyminum* essential oil against *S. oryzae* and *T. castaneum* revealed that mortality was significantly greater for the red flour beetle than for the rice weevil ($p < 0.05$). Nanoencapsulated formulations also had greater insecticidal activity against flour beetles, further suggesting that the red flour beetle is more susceptible to nanoencapsulated essential oils than rice weevils.

The estimated regression lines for adult *S. oryzae* and *T. castaneum* responses to *C. cyminum* essential oil and its nanoencapsulated

formulation indicate that regression lines for rice weevils ($\chi^2 = 0.75$, df = 1, P = 0.38) and for flour beetles ($\chi^2 = 1.79$, df = 1, P = 0.18) were statistically parallel at the 95% confidence level. (Fig. 1).

Repellency of pure and nanoencapsulated essential oil on adult insects

The ANOVA results for repellency activities of *C. cyminum* essential oil and its nanoencapsulated form against adult *S. oryzae* and *T. castaneum* indicated statistically significant differences ($p < 0.01$) among the repellency percentages (Tables 2 and 3). The results showed that repellency caused by conventional cumin essential oil in treated food was initially low in both insects in the early hours, peaked at the 6th hour, and then declined progressively over time. In contrast, repellency assays using nanoencapsulated essential oil showed no repellent activity at low concentrations at early hours. However, repellency increased progressively as the essential oil was slowly released from the nanocapsules. Conventional essential oil showed effective repellency for 6 hours, whereas the nanoencapsulated formulation persisted for 24 hours (Figs. 2 and 3). Moreover, repellency patterns were the same for both rice weevil and flour beetle after exposure to either nanoencapsulated or conventional essential oil. Repellency was higher in both insect species at higher concentrations. For instance, in flour beetles at 6 hours, repellency at 3400 ppm was 17.5% and increased to 55% at 4800 ppm (Tables 2 and 3)

Table 1 LC_{50} and LC_{90} values for contact toxicity of *Cuminum cyminum* essential oil and its nanoencapsulated formulation against *Sitophilus oryzae* and *Tribolium castaneum.*

Insect	Formulation type	N	P-value	χ^2 (df)	Slope ± SE	LC_{50} (ppm) (95% CI)	LC_{90} (ppm) (95% CI)
S. oryzae	Pure essential oil	200	0.784	1.073 (3)	4.68 ± 1.05	11,488 (9,688 – 12,622)	21,562 (18,307 – 31,946)
	Nanoencapsulated oil	200	0.914	0.521 (3)	3.56 ± 0.69	810 (681 – 913)	1,856 (1,500 – 2,901)
T. castaneum	Pure essential oil	200	0.963	0.282 (3)	3.72 ± 0.88	9,194 (7,228 – 10,379)	20,289 (20,116 – 34,373)[1]
	Nanoencapsulated oil	200	0.249	4.119 (3)	2.53 ± 0.41	297 (221 – 362)	954 (751 – 1,433)

CI: Confidence intervals. [1]LC_{90} values exceeding the tested concentration range are extrapolated estimates. The approximate lower confidence limit is close to the point estimate and interpreted with caution.

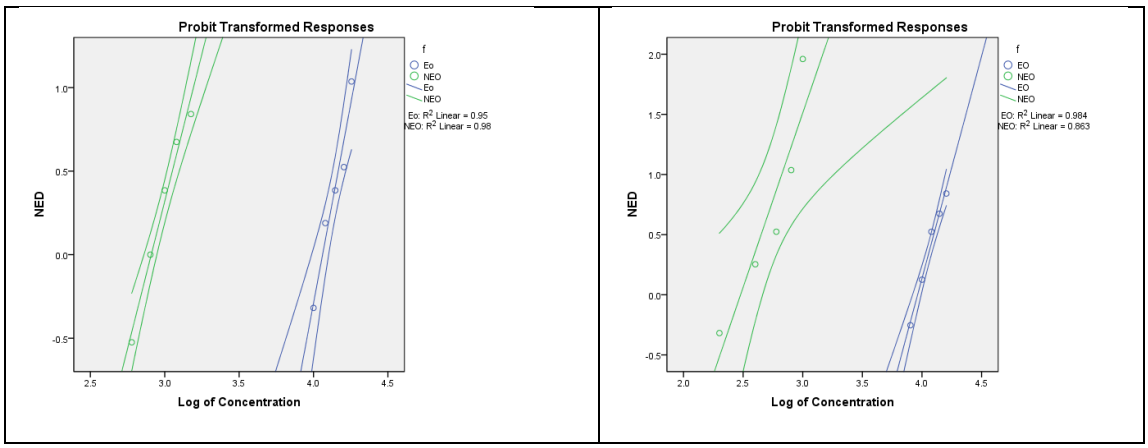

Figure 1 The lethal probit of *Cuminum cyminum* essential oil and its nano-encapsulated form on *Sitophilus oryzae* (left) and *Tribolium castaneum* (right).

Table 2 Repellency of *Cuminum cyminum* essential oil and its nanoencapsulated formulation against *Sitophilus oryzae* at different exposure times.

		% Repellency (Mean ± SE)1				
Formulation	Concen. (ppm)	1 h	3 h	6 h	12 h	24 h
Pure essential oil	2000	1.3 ± 0.3 b	1.3 ± 0.3 d	13.8 ± 2.4 d	12.5 ± 3.2 e	10.0 ± 3.5 d
	2800	5.0 ± 2.0 b	7.5 ± 1.4 cd	17.5 ± 1.4 cd	20.0 ± 3.5 de	10.0 ± 4.1 d
	3100	6.3 ± 2.4 b	16.3 ± 1.3 bc	27.5 ± 2.5 bc	23.8 ± 2.4 de	3.8 ± 2.4 d
	3500	20.0 ± 2.0 a	23.8 ± 1.3 b	33.8 ± 1.3 b	27.5 ± 1.4 cd	6.3 ± 6.3 d
	4000	22.5 ± 3.2 a	35.0 ± 0.0 a	52.5 ± 3.2 a	52.5 ± 3.5 ab	17.5 ± 1.4 d
Nanoencapsulated EO	2000	0.0 ± 0.0 b	3.8 ± 2.4 d	11.3 ± 3.8 d	11.3 ± 4.3 e	36.3 ± 3.1 c
	2800	1.3 ± 0.3 b	6.3 ± 2.4 d	16.3 ± 2.4 cd	18.8 ± 1.3 de	51.3 ± 3.1 c
	3100	0.0 ± 0.0 b	10.0 ± 2.9 cd	22.5 ± 2.5 bcd	38.8 ± 2.4 bc	75.0 ± 2.0 b
	3500	1.3 ± 0.3 b	8.8 ± 2.4 cd	16.3 ± 2.4 cd	40.0 ± 0.0 bc	93.8 ± 2.4 a
	4000	0.0 ± 0.0 b	8.8 ± 1.3 cd	18.8 ± 2.4 cd	57.5 ± 4.8 a	97.5 ± 1.4 a
F		24.54	31.08	23.94	29.37	126.97
df (t.e)		9, 30	9, 30	9, 30	9, 30	9, 30
P-value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Means with the same letters within a column indicate no significant difference (Tukey's test, $P < 0.05$).

Table 3 Repellency of *Cuminum cyminum* essential oil and its nanoencapsulated formulation against *Tribolium castaneum* at different exposure times.

		% Repellency (Mean ± SE)1				
Formulation	Concen. (ppm)	1 h	3 h	6 h	12 h	24 h
Pure Essential oil	3400	6.3 ± 1.3 bc	7.5 ± 1.4 de	17.5 ± 6.0 cde	17.5 ± 3.5 e	10.0 ± 3.5 d
	3800	10.0 ± 0.0 b	13.8 ± 1.3 cd	23.8 ± 1.3 bcd	25.0 ± 3.5 de	12.5 ± 2.5 d
	4100	5.0 ± 0.0 bc	20.0 ± 2.0 bc	27.5 ± 1.4 bcd	28.8 ± 3.8 cd	10.0 ± 3.5 d
	4500	22.5 ± 1.4 a	27.5 ± 1.4 ab	37.5 ± 3.2 b	32.5 ± 1.4 cd	15.0 ± 6.0 d
	4800	25.0 ± 3.5 a	36.0 ± 1.3 a	55.0 ± 2.0 a	51.0 ± 2.4 ab	20.0 ± 2.0 d
Nanoencapsulated EO	3400	0.0 ± 0.0 c	3.8 ± 2.4 e	6.3 ± 3.8 e	26.0 ± 1.3 de	40.0 ± 5.3 c
	3800	0.0 ± 0.0 c	6.3 ± 1.3 de	8.0 ± 2.4 e	31.0 ± 2.3 cd	47.5 ± 1.4 c
	4100	1.3 ± 1.3 c	10.0 ± 0.0 de	15.0 ± 2.0 de	40.0 ± 2.0 bc	68.0 ± 2.8 b
	4500	1.3 ± 1.3 c	15.0 ± 0.0 cd	23.8 ± 1.3 bcd	46.0 ± 1.3 ab	80.0 ± 2.0 b
	4800	3.0 ± 2.4 bc	7.0 ± 3.5 de	31.0 ± 2.4 bc	55.0 ± 2.0 a	98.0 ± 1.8 a
F		33.33	28.87	24.57	24.31	102.51
df (t, e)		9, 30	9, 30	9, 30	9, 30	9, 30
P-value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Means with the same letters within a column indicate no significant difference (Tukey's test, $P < 0.05$).

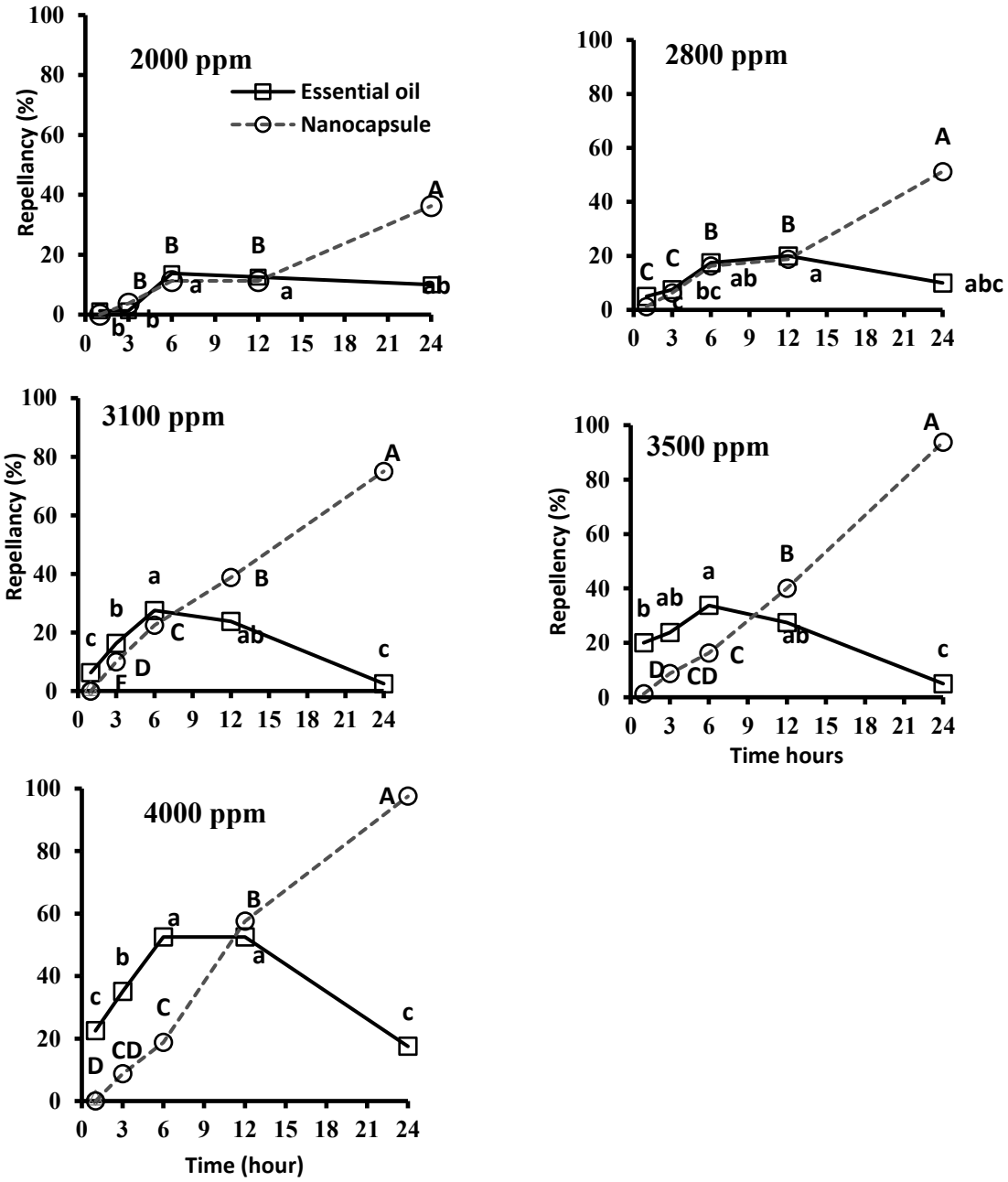

Figure 2 Repellency of different concentrations of essential oil and nanocapsule formulation containing *Cuminum cyminum* essential oil on *Sitophilus oryzae* over different time periods.

Discussion

Plant-derived essential oils are increasingly considered suitable alternatives to synthetic insecticides in stored-product protection because they have low mammalian toxicity, natural origins, and rapid environmental degradation. However, high volatility, rapid oxidation, low persistence, and inconsistent efficacy under storage conditions limit their application in stored-product systems (Isman, 2006; Rajendran and Sriranjini, 2008; Demeter

et al., 2021). These constraints are particularly critical in stored-grain ecosystems, where prolonged protection against internal and external feeders is essential. Therefore, improving the stability and persistence of essential oils is a key step toward their practical implementation in stored-product pest management.

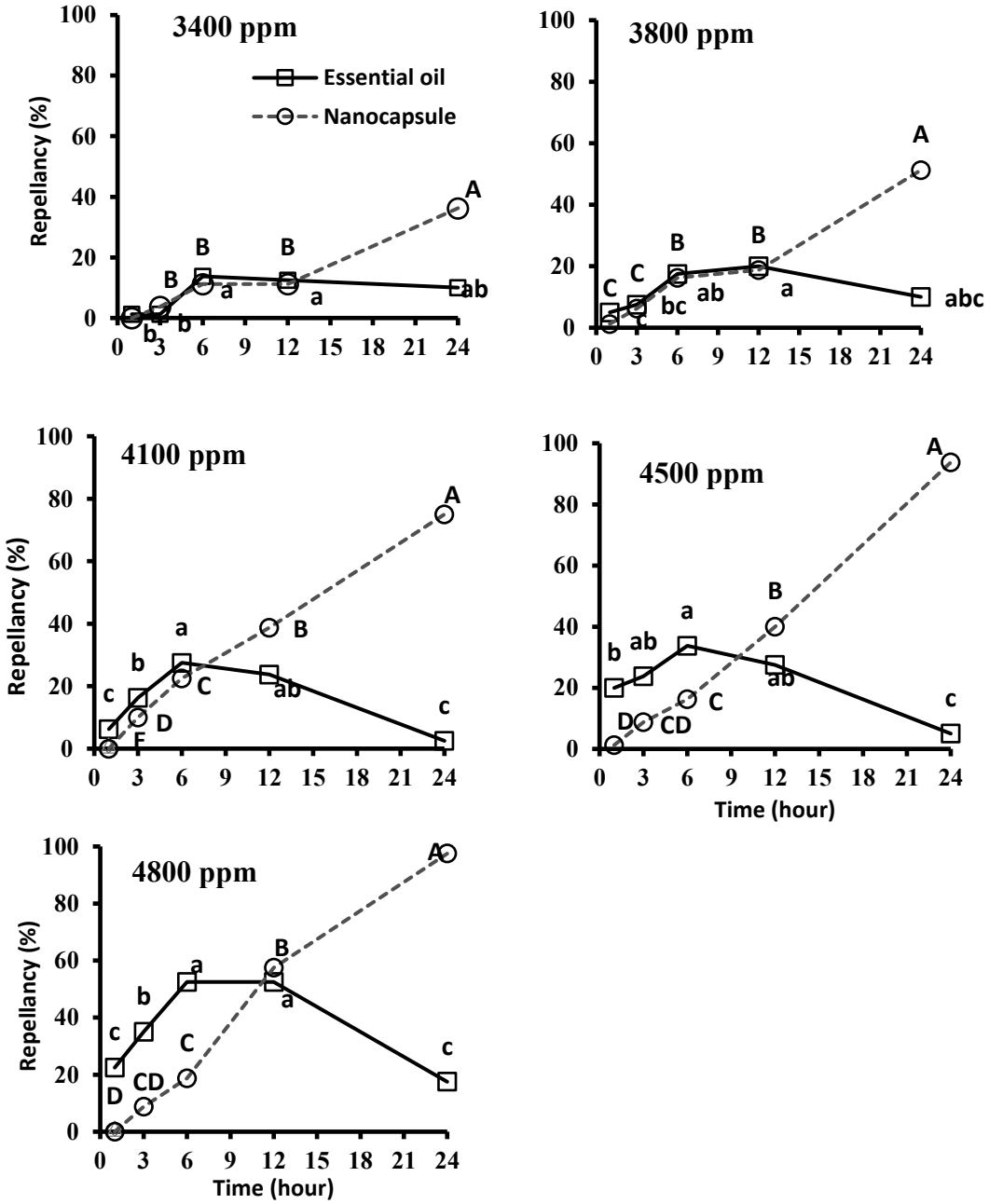

Figure 3 The percentage of repellency of different concentrations of essential oil and nanocapsule formulation containing *Cuminum cyminum* essential oil on *Tribolium castaneum* over different time periods.

In the present study, nanoencapsulation of essential oil derived from *C. cyminum* was evaluated as a strategy to enhance its insecticidal performance against two major stored-product pests, *T. castaneum* and *S. oryzae*. These species are among the most economically important stored-grain pests worldwide, causing quantitative and qualitative losses during storage. Because *S. oryzae* develops inside grains and *T. castaneum* inhabits flour and processed products, effective control requires sustained contact activity. Nanoencapsulation is rational here because it may reduce rapid evaporation and degradation of volatile constituents, maintaining effective concentrations over longer periods.

Contact toxicity results further emphasized the advantages of nanoencapsulation. Direct spraying of the nanoformulation onto adults of *S. oryzae* and *T. castaneum* resulted in significantly higher mortality compared with the pure essential oil. Enhanced dispersion in water, reduced surface tension, and improved adhesion of nanocapsules to the insect cuticle likely contributed to this effect. Earlier studies have reported similar improvements in the contact activity of formulated essential oils (Negahban *et al*., 2011; Ziaee *et al*., 2014). However, it should also be noted that a blank formulation containing the wall material, emulsifier, and other formulation components without the essential oil was not evaluated in this study; therefore, non-specific effects of the formulation matrix cannot be fully excluded, and future studies should include such a control to isolate the contribution of the encapsulated essential oil.

Repellency assays revealed distinct release dynamics between formulations. Pure *C. cyminum* essential oil showed stronger repellency in the first hours after application, likely due to rapid volatilization of active compounds. However, repellency decreased over time. In contrast, the nanoencapsulated formulation showed low initial repellency but gradually increased and maintained repellent activity up to 24 hours. The temporal repellency pattern, low initial repellency followed by increased repellency, may reflect a slow-release effect. However, direct release and stability measurements were not performed, and controlled release should therefore be considered a possible explanation rather than a demonstrated mechanism. Previous studies have reported high repellent activity of essential oils against stored-product pests (Sahaf *et al*., 2008; Akrami *et al*., 2010; Zimmermann *et al*., 2021), and our results confirm that cumin essential oil also possesses strong repellent properties.

The temporal repellency pattern—low initial repellency followed by increased repellency after 24 h—may be consistent with a slow-release effect. However, direct release and stability measurements were not performed, and controlled release should therefore be considered a possible explanation rather than a demonstrated mechanism.

The overall pattern observed in this study highlights an important trade-off between rapid knockdown and long-term persistence. Pure essential oil provides strong short-term fumigant toxicity because it immediately releases volatile compounds. However, high evaporation rates and oxidative degradation limit its residual activity. Nanoencapsulation, by contrast, moderates the release rate, resulting in lower acute toxicity but extended protection. In stored-product pest management, where infestation pressure is continuous, prolonged persistence may be more valuable than rapid but short-lived toxicity.

Application method also significantly influences efficacy. Direct spraying while the formulation is wet ensures effective coverage and adherence of nanocapsules to insect surfaces. However, after drying, residual contact activity is minimal. Therefore, practical implementation in storage systems should consider timing, exposure conditions, and target life stages of pests.

Nanoencapsulation of *C. cyminum* essential oil enhances its suitability for stored-product pest management by improving contact toxicity under direct application, and prolonging repellency. Although pure essential oil demonstrates stronger initial toxicity, nanoformulations offer greater long-term effectiveness, which is particularly relevant for

controlling *S. oryzae* and *T. castaneum* in storage environments. Further studies under real storage conditions are needed to evaluate residual performance and additional effects, such as anti-oviposition and anti-feeding activities, to fully assess the potential of cumin nanoformulations in integrated pest management programs.

Conclusion

Under laboratory conditions, nanoencapsulation improved the contact toxicity of *C. cyminum* essential oil and prolonged repellency up to 24 h compared with the pure oil against stored-product pests such as *S. oryzae* and *T. castaneum*. Therefore, nanoformulations may represent an effective strategy to enhance performance, reduce the required dosage of active ingredients, and strengthen the role of plant essential oils in integrated pest management programs. Nevertheless, further investigations are required to evaluate long-term effects and practical applicability under real-world conditions.

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References

Abbott, W. S. 1925. A method for computing the effectiveness of an insecticide. Journal of Economic Entomology, 18: 265-267.

Abdelgaleil, S. A. M., Gad, H. A., Ramadan, G. R., El-Bakry, A. M. and El-Sabrout, A. M. 2024. Monoterpenes: chemistry, insecticidal activity against stored product insects and modes of action—a review. International Journal of Pest Management, 70: 267-289.

Aghazadeh, A., Negahban, M. and Fathipour, Y. 2025. Sublethal impacts of a commercial botanical pesticide (Salpipest®) containing nanoencapsulated essential oil of wild pistachio on demographic parameters of the predatory mite *Amblyseius swirskii* feed on greenhouse whitefly. Neotropical Entomology, 54: 27.

Akrami, H., Moharramipour, S. and Imani, S. 2010. Repellent activity of two medicinal plant essential oils on *Tribolium castaneum* and *Ephestia kuehniella*. Journal of Stored Product Protection. 10th International Working Conference on Stored Product Protection, 27 June to 2 July 2010, Estoril, Portugal. DOI: https://doi.org/10.5073/jka.2010.425.167.274.

Atwal, A. S. 1976. Insect pests of stored grain and other products. In: Agricultural Pests of India and South-East Asia. Kalyani Publisher, New Delhi, India, pp. 389-415.

Baloch, U. K. 1992. Integrated Pest Management in Food Grains. Food and Agriculture Organization of the United Nations and Pakistan Agricultural Research Council, Islamabad, Pakistan, 117.

Brown, S. J., Shippy, T. D., Miller, S., Bolognesi, R., Beeman, R. W., Lorenzen, M. D., Bucher, G., Wimmer, E. A. and Klingler, M. 2009. The red flour beetle, *Tribolium castaneum* (Coleoptera): a model for studies of development and pest biology. Cold Spring Harbor Protocols, 2009(8): pdb.emo126. https://doi.org/10.1101/pdb.emo126.

Campbell, J. F., Athanassiou, C. G., Hagstrum, D. W. and Zhu, K. Y. 2022. *Tribolium castaneum*: a model insect for fundamental and applied research. Annual Review of Entomology, 67: 347-365.

Dars, F., Rustamani, M. A., Khuro, R. D., Baloch, H. B. 2001. Effect of wheat grain moisture on infestation of red flour beetle, *Tribolium castaneum* (Herbst). Pakistan Journal of Zoology, 33: 189-200.

Demeter, S., Lebbe, O., Hecq, F., Nicolis, S. C., Kenne Kemene, T., Martin, H., Fauconnier, M. L. and Hance, T. 2021. Insecticidal activity of 25 essential oils on the stored product pest, *Sitophilus granarius*. Foods, 10: 200.

Farina, P. and Conti, B. 2024. Liabilities of essential oils as insect repellents. Current Opinion in Environmental Science and Health, 40: 100564.

Hamed, M., Khattak, S. U. 1985. Red flour beetle: Development and losses in various

stored food stuffs. Sarhad Journal of Agriculture, 1: 97-101.

Isman, M. B. 2006. Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. Annual Review of Entomology, 51: 45-66.

Isman, M. B. 2020. Commercial development of plant essential oils and their constituents as active ingredients in bioinsecticides. Phytochemistry Reviews, 19: 235-241.

Khattak, S. U. K., Khatoon, R., Wahid, M. 1999. Insect attack and nutritional losses in stored dried fruits. The Nucleus, 6: 113-116.

Lai, F., Wissing, S. A., Müller, R. H., Fadda, A. M. 2006. *Artemisia arborescens* L. essential oil–loaded solid lipid nanoparticles for potential agricultural application: Preparation and characterization. AAPS PharmSciTech, 7(1): E10–E18. https://doi.org/10.1208/pt070102.

Lee, B. H., Choi, W. S., Lee, S. E., Park, B. S. 2001. Fumigant toxicity of essential oils and their constituent compounds towards the rice weevil, *Sitophilus oryzae* (L.). Crop Protection, 20: 317-320.

Liu, C. H., Mishra, A. K., Tan, R. X., Tang, C., Yang, H. and Shen, Y. F. 2006. Repellent and insecticidal activities of essential oils from *Artemisia princeps* and *Cinnamomum camphora* and their effect on seed germination of wheat and broad bean. Bioresource technology, 97: 1969-1973.

Lowry, G. V., Avellan, A. and Gilbertson, L. M. 2019. Opportunities and challenges for nanotechnology in the agri-tech revolution. Nature nanotechnology, 14: 517-522.

Maji, T., Baruah, I., Dube, S. and Hussain, M. 2007. Microencapsulation of *Zanthoxylum limonella* oil (ZLO) in glutaraldehyde crosslinked gelatin for mosquito repellent application. Bioresource Technology, 98: 840-844.

Moharramipour, S. and Negahban, M. 2014. Plant essential oils and pest management. In: Sahayaraj, K. (Ed.), Basic and Applied Aspects of Biopesticides, Springer, New Delhi, India, pp. 129-153.

Negahban, M., Moharramipour, S. and Sefidkon, F. 2007. Fumigant toxicity of essential oil from *Artemisia sieberi* Besser against three stored-product insects. Journal of Stored Products Research, 43: 123-128.

Negahban, M., Moharramipour, S., Zandi, M. and Hashemi, S. A. 2011. Insecticidal activity of nano capsules of essential oil on *Tribolium castaneum* (Herbst). Proceedings of the Global Conference on Entomology (CGE), Chiang Mai, Thailand, 605.

Negahban, M., Moharramipour, S., Zandi, M. and Hashemi, S. A. 2012a. Fumigant properties of nano-encapsulated essential oil from Artemisia sieberi on Tribolium castaneum. In: Navarro, S., Banks, H. J., Jayas, D. S., Bell, C. H., Noyes, R. T., Ferizli, A. G., Emekci, M., Isikber, A. A. and Alagu-sunda-ram, K. (Eds.), Proceedings of the 9th International Conference on Controlled Atmosphere and Fumigation in Stored Products, Antalya, Turkey. 15 -19 October 2012, ARBER Professional Congress Services, Turkey pp: 101-105.

Negahban, M., Moharramipour, S., Zandi, M., Hashemi, S. A. and Ziaee, F. 2012b. Nano-insecticidal activity of essential oil from *Cuminum cyminum* on *Tribolium castaneum*. In: Navarro, S., Banks, H. J., Jayas, D. S., Bell, C. H., Noyes, R. T., Ferizli, A. G., Emekci, M., Isikber, A. A. and Alagu Sunda Ram, K. (Eds.), Proceedings of the 9th International Conference on Controlled Atmosphere and Fumigation in Stored Products, Antalya, Turkey. 15-19 October 2012, ARBER Professional Congress Services, Turkey pp: 63-68.

Negahban, M., Moharramipour, S., Zand, M. and Hashemi, S. A. 2013a. Repellent activity of nanoencapsulated essential oil of *Artemisia sieberi* Besser on *Plutella xylostella* L. larvae. Iranian Journal of Medicinal and Aromatic Plants. 29(4): 909-924.

Negahban, M., Moharramipour, S., Zandi, M. and Hashemi, S. A. 2013b. Efficiency of nanoencapsulated essential oil of *Artemisia sieberi* Besser on nutritional indices of *Plutella xylostella*. Iranian Journal of Medicinal and Aromatic Plants. 29(3): 692-708.

Nuruzzaman, M. B., Rahman, M. M., Liu, Y. and Naidu, R. 2016. Nanoencapsulation,

nano-guard for pesticides: A new window for safe application. Journal of Agricultural and Food Chemistry, 64: 1447-1483. https://doi.org/10.1021/acs.jafc.5b05214.

Pillmoor, J. B., Wright, K. and Terry, A. S. 1993. Natural products as a source of agrochemicals and leads for chemical synthesis. Pesticide Science, 39: 131-140.

Rajendran, S. and Sriranjini, V. 2008. Plant products as fumigants for stored-product insect control. Journal of Stored Products Research, 44: 126-135.

Sacchetti, G., Maietti, S., Muzzoli, M., Scaglianti, M., Manfredini, S., Radice, M. and Bruni, R. 2005. Comparative evaluation of 11 essential oils of different origin as functional antioxidants, antiradicals and antimicrobials in foods. Food Chemistry, 91: 621-632.

Sahaf, B. Z., Moharramipour, S., Meshkatalsadat, M. H. and Filekesh, E. 2008. Repellent activity and persistence of the essential oils from *Carum copticum* and *Vitex pseudo-negundo* on *Tribolium castaneum*. Integrated Protection of Stored Products, 40: 205-210.

Shakarami, J., Kamali, K., Moharramipour, S. and Meshkatalsadat, M. 2003. Fumigant toxicity and repellency of the essential oil of *Artemisia aucheri* on four species of stored products pests. Applied Entomology Phytopathology, 71: 61-75.

Turek, C. and Stintzing, F. C. 2013. Stability of essential oils: a review. Comprehensive Reviews in Food Science and Food Safety, 12: 40-53.

Wang, H., Jiang, Z., Feng, J. and Zhang, X. 2006. Inhibitory effects of seven essential oils against *Botrytis cinerea*. Plant Protection, 33: 111-114.

Wilson, J. A. and Isman, M. B. 2006. Influence of essential oils on toxicity and pharmacokinetics of the plant toxin thymol in the larvae of *Trichoplusia ni*. The Canadian Entomologist, 138: 578-589.

Ziaee, M., Moharramipour, S. and Mohsenifar, A. 2014. Toxicity of *Carum copticum* essential oil-loaded nanogel against *Sitophilus granarius* and *Tribolium confusum*. Journal of Applied Entomology, 138: 763-771.

Zimmermann, R. C., de Carvalho Aragao, C. E., de Araújo, P. J. P., Benatto, A., Chaaban, A., Martins, C. E. N., do Amaral, W., Cipriano, R. R. and Zawadneak, M. A. 2021. Insecticide activity and toxicity of essential oils against two stored-product insects. Crop Protection, 144: 105575.

خواص حشره‌کشی اسانس نانوکپسوله شده زیره سبز روی شپشه برنج *Sitophilus oryzae* و شپشه قرمز آرد *Tribolium castaneum*

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چکیده: شپشه برنج، *Sitophilus oryzae* L.، و سوسک قرمز آرد، *Tribolium castaneum* (Herbst)، از آفات مهم انباری با پراکندگی جهانی هستند که خسارت قابل‌توجهی به محصولات کشاورزی وارد می‌کنند. توجه فزاینده‌ای به استفاده از اسانس‌های گیاهی به‌عنوان جایگزین‌های طبیعی و سازگار با محیط‌زیست معطوف شده است. با این حال، حلالیت کم در آب، حساسیت بالا به اکسیداسیون و ناپایداری آن‌ها، کاربرد مستقیم این ترکیبات را محدود می‌کند. در این راستا، به‌کارگیری فناوری‌های پیشرفته فرمولاسیون، رویکردی مؤثر برای افزایش پایداری و کارایی اسانس‌های گیاهی در کنترل آفات ارائه می‌دهد. در مطالعه حاضر، اسانس گیاه زیره سبز *Cuminum cyminum* L. با استفاده از روش پلیمریزاسیون *in-situ*(درجا) امولسیون روغن/آب (O/W) در مقیاس نانو ریزپوشانی شد. سمّیت تماسی و فعالیت دورکنندگی اسانس خالص و فرموله شده علیه حشرات کامل *S. oryzae* و *T. castaneum* ارزیابی گردید. تمام آزمایش‌ها با چهار تکرار و همراه با تیمار شاهد، تحت شرایط کنترل شده دمای ۱ ± ۲۵ درجه سلسیوس، رطوبت نسبی ۵ ± ۶۵ درصد و در تاریکی انجام شدند. در آزمون‌های سمّیت تماسی به روش محلول‌پاشی، نانوفرمولاسیون کارایی برتری از خود نشان داد. به‌علاوه، آزمون‌های فعالیت دورکنندگی آشکار ساختند که درحالی‌که اسانس خالص دورکنندگی قوی‌تری در کوتاه مدت (تا ۶ ساعت پس از قرارگیری در معرض تیمار) داشت، اسانس فرموله شده پس از ۲۴ ساعت به‌طور معنی‌داری دورکنندگی بالاتری از خود نشان داد. به‌طور کلی، نانو ریزپوشانی در مقایسه با اسانس خالص منجر به بهبود سمّیت تماسی و دورکنندگی علیه آفات انباری شد. لذا، نتایج این مطالعه بر پتانسیل امیدوارکننده نانوفرمولاسیون‌های گیاه بنیاد برای مدیریت پایدار آفات تأکید دارد.

واژگان کلیدی: اسانس، سمّیت تدخینی، نانو ریزپوشانی، *Sitophilus oryzae*، *Tribolium castaneum*