



RESEARCH ARTICLE

Management of lesser grain borer, *Rhyzopertha dominica* through nano bioformulations in stored rice

Anu K V^{1,2}, Rajasri Mandal^{2*}, G S Panduranga², Rani K S³ & T N V K V Prasad⁴

¹Department of Entomology, ICAR-Central Institute for Cotton Research, Nagpur 440 010, Maharashtra, India

²Department of Entomology, Acharya N. G. Ranga Agricultural University Lam, Guntur 522 034, Andhra Pradesh, India

³National silkworm seed organization, Central Silk Board, Bengaluru 560 068, Karnataka, India

⁴Nanotechnology Laboratory, Institute of Frontier Technologies, Regional Agricultural Research Station, Acharya N. G. Ranga Agricultural University (ANGRAU), Tirupati 517 502, Andhra Pradesh, India

*Correspondence email - m.rajasri@angrau.ac.in

Received: 09 September 2025; Accepted: 28 April 2026; Available online: Version 1.0: 14 September 2026

Cite this article: Anu KV, Rajasri M, Panduranga GS, Rani KS, Prasad TNVKV. Management of lesser grain borer, *Rhyzopertha dominica* through nano bioformulations in stored rice. Plant Science Today. 2026;13(sp5):01–12. <https://doi.org/10.14719/pst.11699>

Abstract

Nanoencapsulation of botanical insecticides has emerged as a promising strategy to improve the efficacy and stability of plant-derived compounds in stored-product pest management. The present study aimed to develop and evaluate nano silica-encapsulated formulations of neem (*Azadirachta indica* A. Juss.) oil, acorus (*Acorus calamus* L.) oil and the chemical insecticide imidacloprid for the management of *Rhyzopertha dominica*, a major pest of stored rice. Laboratory bioassays were conducted using contact toxicity and diet incorporation methods, followed by storage studies to assess long-term protective efficacy. The nano formulations were evaluated at different concentrations and adult mortality was determined using corrected mortality analysis. In contact toxicity assays, LC₅₀ values were 0.16 % for nano neem and nano acorus oils and 0.02 % for nano imidacloprid, compared with 0.17 %, 0.17 % and 0.03 %, respectively, for their conventional formulations. In the diet incorporation method, LC₅₀ values for nano neem, nano acorus and nano imidacloprid were 0.25 %, 0.26 % and 0.10 %, respectively, whereas conventional formulations recorded higher LC₅₀ values of 0.35 %, 0.47 % and 0.35 %. Storage studies revealed that nano silica-based formulations effectively protected rice seeds from insect infestation for up to five months without seed damage or weight loss. Furthermore, treated seeds maintained high germination percentage and seedling vigour throughout the storage period. The findings demonstrate that nanoencapsulation enhances the insecticidal efficiency and persistence of botanical oils while maintaining seed quality, highlighting its potential as a sustainable approach for protecting stored grains.

Keywords: bioassay; contact toxicity; diet incorporation; germination; nano bioformulation; nano encapsulation; seedling vigour

Introduction

Stored products insects infest and damage stored grains, cereals, pulses, dried fruits and other commodities, leading to substantial economic losses worldwide. Among these pests, *Rhyzopertha dominica*, commonly known as the lesser grain borer, is one of the most destructive pests of stored grains. It infests a wide range of stored commodities and causes serious losses by boring into kernels and feeding internally (1). The eggs hatch in 5.40 ± 0.50 days with an approximate hatch rate of 80 % and larvae develop through four instars over 24.35 ± 2.83 days, followed by pre-pupal and pupal stages lasting 1.00 ± 0.00 and 3.85 ± 0.87 days, respectively (2). The relatively short life cycle, high reproductive potential and concealed larval feeding inside grains reduce the effectiveness of conventional contact insecticides and necessitate the development of improved pest management strategies. This insect belongs to the family Bostrichidae and is considered an important internal feeder of stored rice, resulting in considerable quantitative and qualitative losses (3).

In recent years, essential oils (EOs) have attracted increasing attention as potential alternatives for the management of stored-product pests due to their natural origin and insecticidal properties (4, 5). Essential oils contain diverse bioactive compounds such as terpenoids, phenols and ketones, which exhibit insecticidal, repellent and antifeedant activities (6). Among these compounds, monoterpenoids have received particular attention because of their strong fumigant toxicity against stored-product insects (7). Essential oils can disrupt insect physiology, behaviour and development and several studies have demonstrated their effectiveness against a wide range of storage pests including beetles, weevils, moths and mites. Their modes of action include contact toxicity, fumigation and repellent effects, which help deter pests from infesting stored commodities (8).

Despite these advantages, the practical application of essential oils is often limited by their high volatility, rapid degradation and relatively short residual activity. In addition, their effectiveness may vary depending on the type of essential oil, target pest species, environmental conditions and application methods (9).

Conventional fumigation with Phosphine has long been the primary method for controlling stored-grain pests. However, its effectiveness has been increasingly challenged due to the development of insect resistance and growing concerns regarding environmental contamination and food safety. Resistance to phosphine has been widely reported in several stored-grain pests, including *R. dominica* (10, 11). Furthermore, the excessive use of synthetic pesticides can result in toxic residues in food products, harmful effects on non-target organisms and potential risks to human health and the environment. These concerns highlight the urgent need for safer, eco-friendly and sustainable pest management alternatives (12). In this context, plant-derived essential oils have emerged as promising candidates because of their biodegradability, lower environmental persistence and broad spectrum of bioactivity against storage pests (13).

Recent advances in nanotechnology have opened new opportunities for improving the efficacy of botanical pesticides. Nano-encapsulation technologies have been shown to enhance the stability, bioavailability and insecticidal efficiency of plant-derived compounds against stored-grain pests (14, 15). Nano-encapsulation enables controlled and sustained release of active compounds, allowing prolonged exposure of pests to insecticidal agents (16, 17). This controlled release improves the persistence of essential oil activity and enhances pest control efficacy. In addition, nanoscale particles can facilitate targeted delivery of active compounds to pest habitats, thereby improving application efficiency, minimising off-target effects and reducing the amount of active ingredient required (18, 19). The small particle size also enables better penetration into cracks, crevices and other hidden locations where storage pests often reside, improving coverage and contact with target insects (20).

Therefore, the present study aimed to develop nano silica-encapsulated formulations of neem and acorus oils and evaluate their insecticidal efficacy against *R. dominica* infesting stored rice, while also assessing their impact on seed quality parameters during storage.

Materials and Methods

Insect collection

The initial mother culture of lesser grain borer, *R. dominica* insects were collected from rice storage godown, Regional Agricultural Research Station, Tirupati Andhra Pradesh. The collected insects were brought to the laboratory, Department of Entomology, S.V. Agricultural College, Tirupati, ANGRAU and were mass multiplied on rice seed under laboratory conditions at 25 ± 2 °C and 65 % RH.

Maintenance of *Rhyzopertha dominica* insect culture

The mass multiplication of *R. dominica* was carried out in the plastic containers (11 cm × 8 cm) containing freshly harvested rice. The adult beetles of mixed sexes were released and the container was covered with muslin cloth and secured with rubber band. The plastic jars were kept undisturbed for 30–35 days until the emergence of adults and the freshly emerged adults were used for bioassay and storage studies.

Nano silica encapsulation of plant products and imidacloprid

Commercial neem oil formulation, Neemazal (10000 ppm), Acorus (*Acorus calamus* L.) oil and commercial imidacloprid (Confidor 200

SL) were used for bioassay studies. Neem (*Azadirachta indica* A. Juss.) oil was thoroughly mixed in distilled water using magnetic stirrer for 1 hr to obtain homogenised solution. Similarly, acorus oil was dissolved in diluted acetone by keeping on magnetic stirrer for overnight to obtain homogenised solution. A 1 g of nano silica was weighed and dissolved in 100 mL of water and mixed properly by keeping on magnetic stirrer for 15 min. 0.5 g of gum acacia was dissolved in 50 mL of water by keeping on magnetic stirrer for 30 min. Then 10 mL of gum acacia solution was added to 100 mL of prepared nano silica solution. The required concentration of neem oil and acorus oil were added to nano silica: gum acacia solution and kept on magnetic stirrer for mixing to get homogeneous formulation.

Dynamic light scattering (DLS) was performed using a particle sizing system, Horiba Nanoparticle analyser at a wavelength of 633 nm from 4.0 mW, solid-state He-Ne laser at a scattering angle of 170°. Intensity average, volume average and number average diameters were calculated from the auto correlation function using Malvern's Zetasizer Nano 4.2 software utilising a version of the CONTIN algorithm.

Bioassay studies with nano biopesticides and plant products on *Rhyzopertha dominica*

Contact toxicity of plant products and nano formulations were evaluated using filter paper impregnation method against adults of *R. dominica*. Each nano formulation was tested at 5 different concentrations and based on that corrected adult mortality percentage was calculated along with untreated control. A 1 mL of each nano formulation was applied to filter paper in petri plates and allowed for evaporation of solvent. After the evaporation of solvent ten adult *R. dominica* beetles were released into each petri dish and each treatment was replicated four times. Adult mortality was recorded at 24, 48 and 72 hr after treatment (HAT). Adults with no response to prodding by camel brush were considered as dead.

The efficacy of plant products and nano formulations was evaluated against adults of *R. dominica* through diet incorporation method. Each nano formulation was tested at 5 different concentrations and based on that corrected adult mortality percentage was calculated along with untreated control. Freshly harvested, insect free and clean rice variety 'BPT-5204' obtained from KVK, Garikapadu, Krishna district, Andhra Pradesh was used for experimental purpose 25 g of rice seed was poured into plastic containers. The rice seeds were mixed with required concentrations of plant products and the nano-formulations to achieve equal distribution; containers were shaken manually for 5 min. Ten adults were released into each plastic container and replicated four times. The containers were maintained under ambient conditions in the laboratory. The mortality counts were taken after 1, 3, 5, 7 and 15 days after exposure (Fig. 1).

Storage studies with nano biopesticides and plant products on lesser grain borer *Rhyzopertha dominica* in stored rice

Initial seed quality parameters of rice

A fresh seed lot of BPT 5204 rice seed with 100 % germination was used for storage studies. Rice grains were subjected to different treatments with plant products and nano formulations and the seeds were tested for germinability and vigour using paper towel method (21). The initial germination of rice seed was 100 % without any insect damage and recorded high seedling vigour (> 2500).

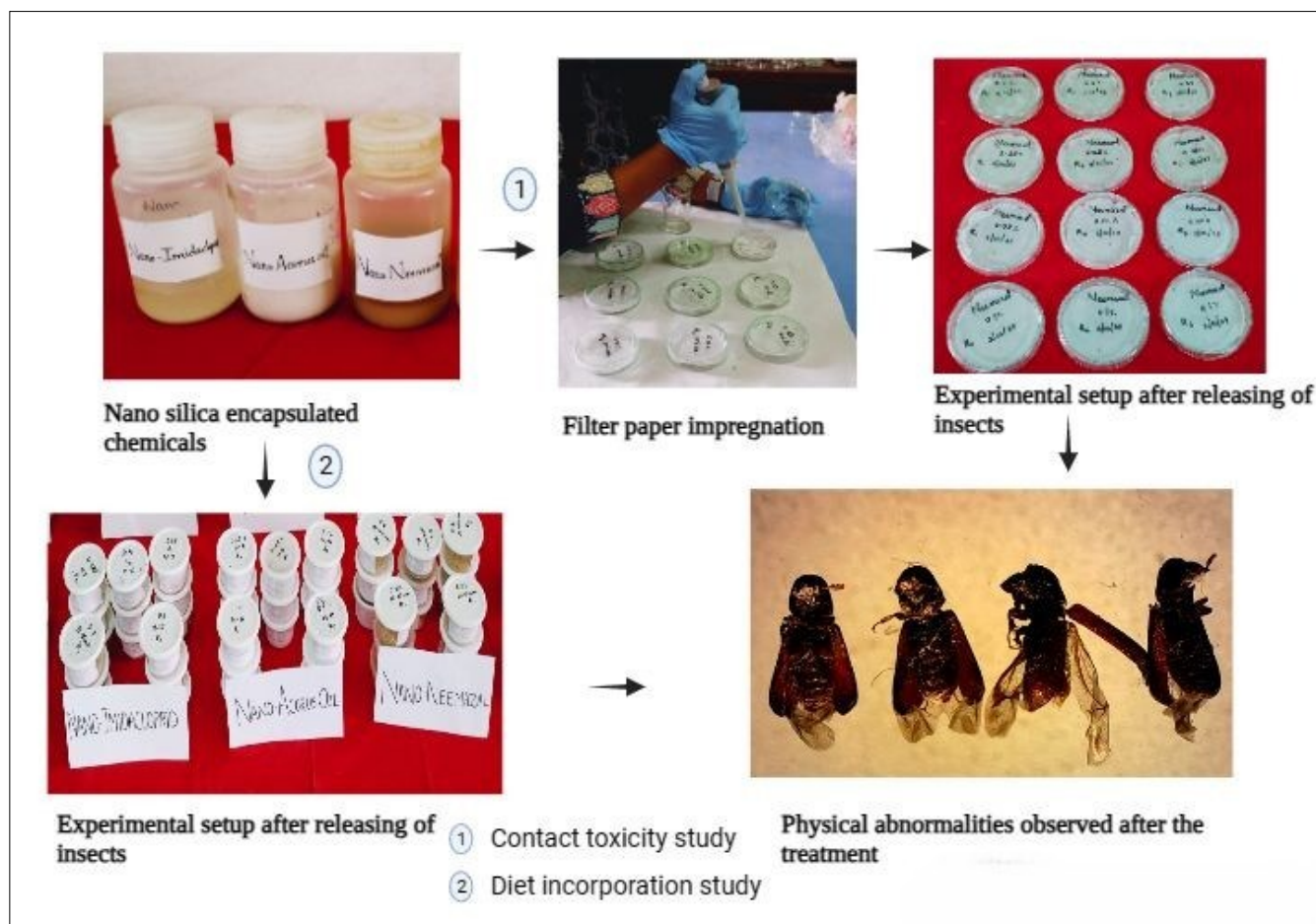


Fig. 1. Contact and diet incorporation studies using nano silica encapsulated bioformulations and their normal formulations.

Germination percentage

Germination test was conducted with germination paper towel method using four replications in the laboratory at room temperature of $25 \pm 2^\circ\text{C}$ and $70 \pm 5\%$ RH. The number of normal seedlings in each replication was counted on 10th day. The germination was calculated and expressed in percentage (22).

$$\text{Germination percentage} = \frac{\text{No. of seeds germinated}}{\text{Total no. of seeds}} \times 100$$

Shoot length (cm)

Ten normal seedlings from each replication were taken for measuring the shoot length from collar region to the tip of the shoot. The average of 10 seedlings was worked out and expressed in centimetres.

Root length (cm)

Ten normal seedlings were used for measuring root length and measured from the collar region to the tip of the main root. The average of 10 roots was worked out and expressed in centimetres.

Total seedling length (cm)

The mean root and shoot length of 10 normal seedlings were added up to get the total seedling length and expressed in centimeters.

Seedling dry weight (mg)

Ten normal seedlings were taken in butter paper and dried in a hot air oven maintained at 80°C temperature for 24 hr. Then, dried seedlings were removed and allowed to cool in a desiccator for 30 min before weighing in an electronic balance. The average weight was calculated and expressed as seedling dry weight in milligram.

Seedling vigor index - I and seedling vigour index - II

The seedling vigour indices were determined by using the following formulae suggested by previous researchers (23).

$$\text{SVI - I} = \text{Germination percentage} \times \text{Seedling length (cm)}$$

$$\text{SVI - II} = \text{Germination percentage} \times \text{Seedling dry weight (g)}$$

$$\text{Seedling vigour index-I} = \text{Per cent germination} \times \text{Seedling length in cm}$$

$$\text{Seedling vigour index-II} = \text{Per cent germination} \times \text{Seedling dry weight in mg}$$

Statistical analysis

The recorded data in percentages was transformed to angular transformed values (24). The experiment was conducted in completely randomised design replicated 4 times and the data recorded was subjected to statistical analysis using IBM SPSS Statistics, Version 26.0 (IBM Corp., Armonk, NY, USA).

Results

Characterisation of nano silica-encapsulated formulations

Nano silica-encapsulated formulations of neem oil, acorus oil and Imidacloprid were characterised using dynamic light scattering and zeta potential analysis. Particle size ranged from 99.2 to 161.1 nm. Nano imidacloprid recorded a mean particle diameter of 161.1 nm, nano neem oil 160.5 nm and nano acorus oil 99.2 nm (Fig. 2). Zeta potential values were -37 mV for nano imidacloprid, -31.4 mV for nano neem oil and -50.5 mV for nano acorus oil, indicating good formulation stability (Fig. 3). Transmission electron microscopy further confirmed the nanoscale morphology of the particles (Fig. 4).

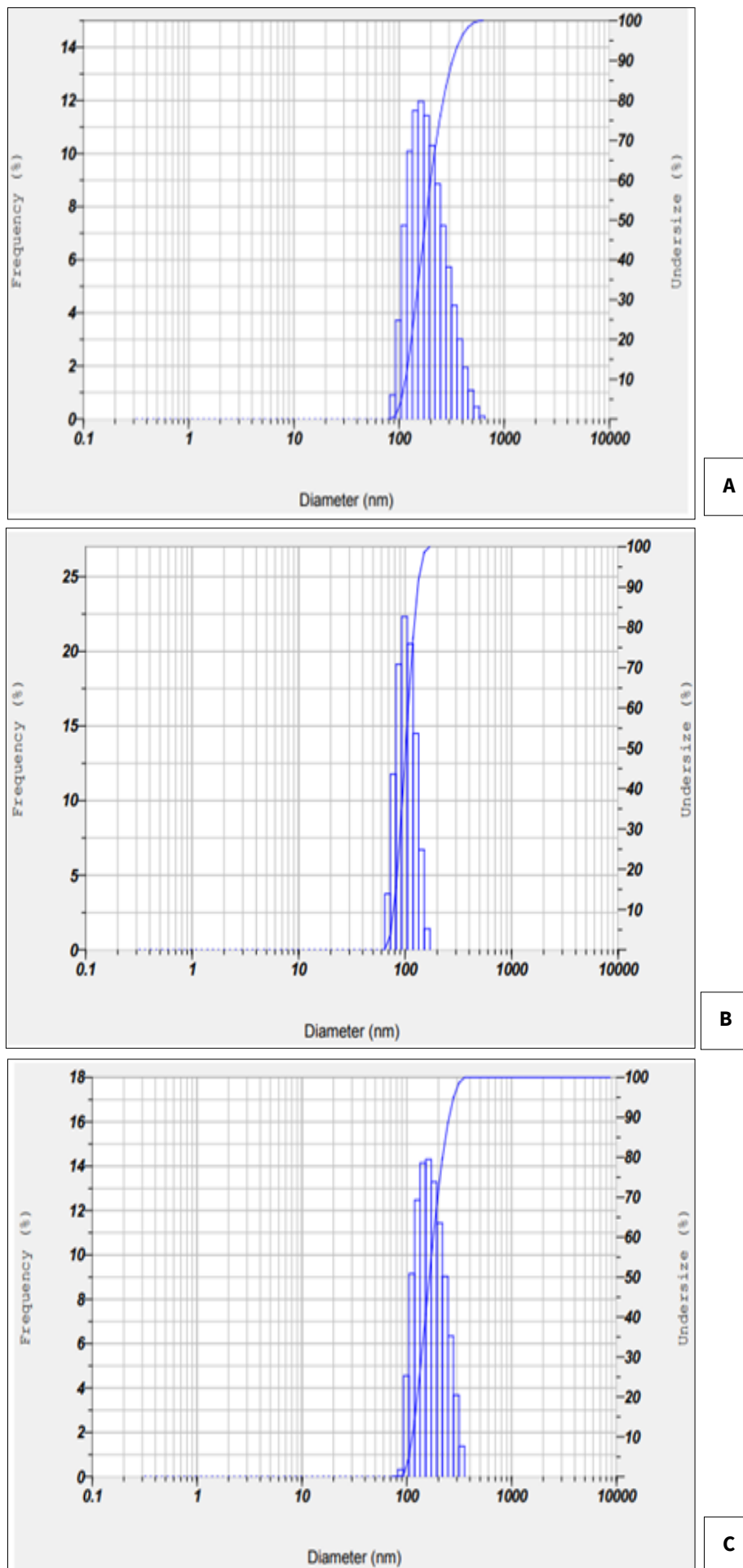


Fig. 2. Dynamic light scattering (DLS) for particle size distribution of different prepared nano formulations using nano particle analyser. A: Nano neem; B: nano Acorus; C: nano imidacloprid.

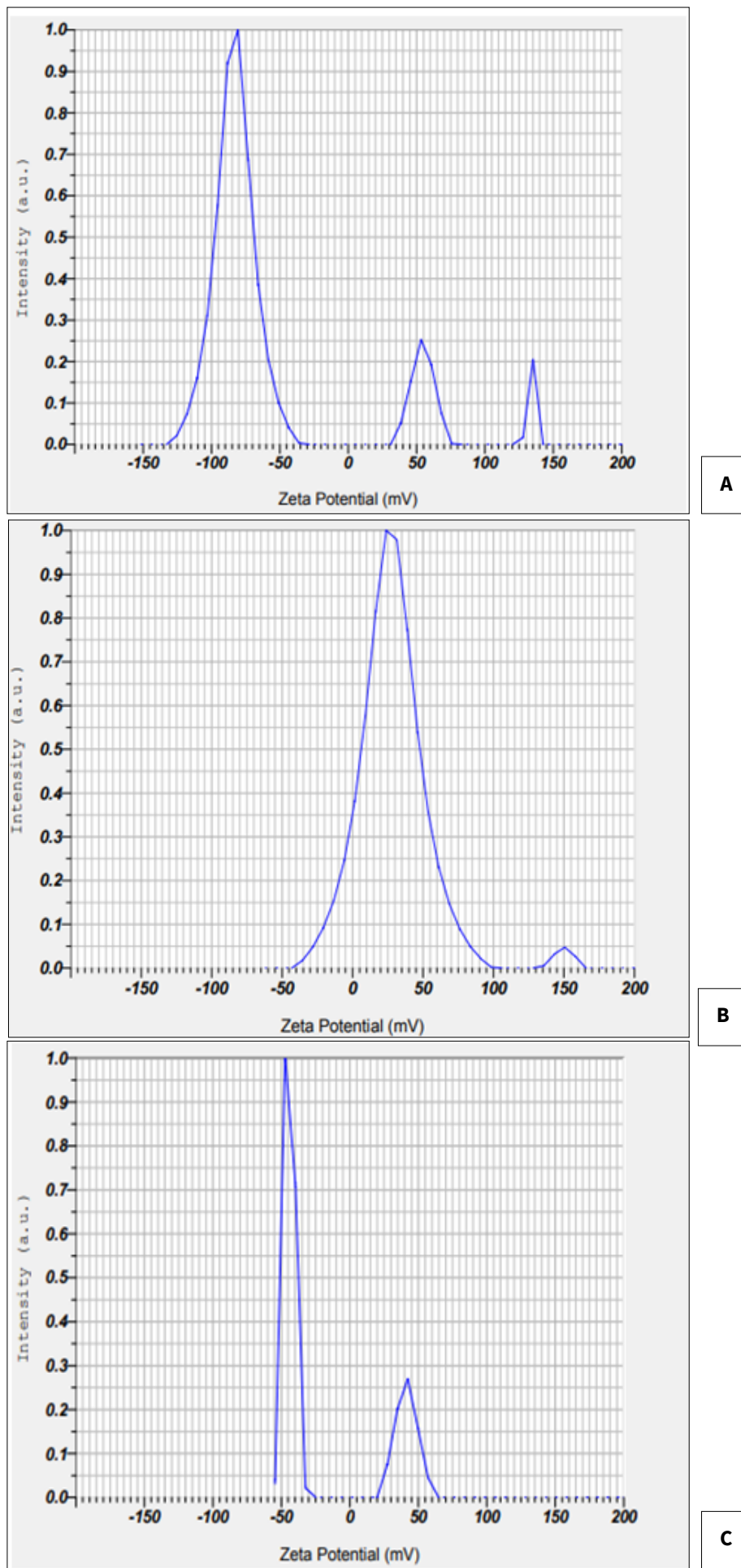


Fig. 3. Dynamic light scattering (DLS) for zeta potential of different prepared nano formulations using nano particle analyser. A: Nano neem; B: nano Acorus; C: nano imidacloprid.

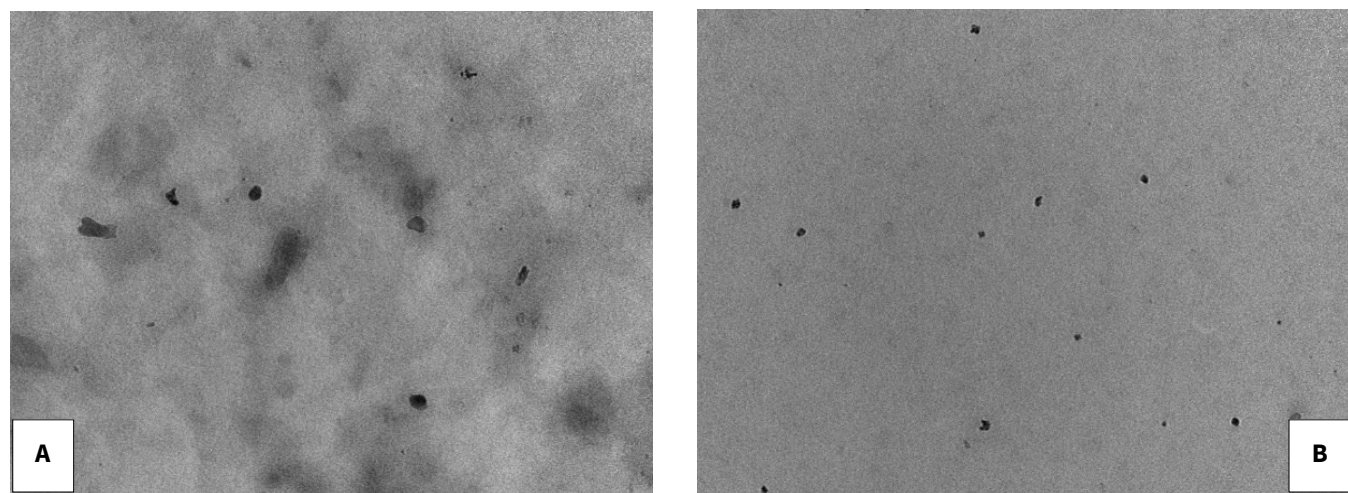


Fig. 4. High resolution electron microscopic images of prepared nano formulations. A: Nano neem oil; B: Nano Acorus oil.

Contact toxicity bioassay

Nano silica-encapsulated formulations showed dose and time dependent toxicity against *R. dominica* using the filter paper impregnation method.

Nano neem oil recorded 100 % mortality at 0.6 % within 24 hr, while lower concentrations resulted in reduced mortality. Complete mortality was observed at 0.6 % and 0.5 % after 72 hr (Table 1). Nano acorus oil recorded 86.67 % mortality at 1 % concentration after 72 hr, with mortality decreasing at lower concentrations (Table 2). Nano imidacloprid exhibited the highest toxicity, producing 83.33 % mortality within 24 hr and 100 % mortality at 72 h at 0.5 % concentration (Table 3).

Probit analysis revealed lower LC_{50} values for nano formulations than conventional formulations. LC_{50} values were 0.16 % for nano neem oil, 0.16 % for nano acorus oil and 0.02 % for nano imidacloprid, compared with 0.17 %, 0.17 % and 0.03 % for their respective conventional formulations (Table 4).

Diet incorporation bioassay

Nano formulations also showed higher insecticidal activity in the diet incorporation method. Nano neem oil achieved 100 % mortality at 0.6 % concentration within 7 days after treatment, while all concentrations resulted in complete mortality by 15 days (Table 5, Fig 5). Nano acorus oil exhibited concentration dependent toxicity, with mortality increasing from 80 % at 0.05 % to 100 % at 1 % concentration by 10 days (Table 6, Fig 6).

Nano imidacloprid showed the highest efficacy, recording 100 % mortality at 7 days at 0.7 % concentration and complete mortality at all concentrations by 10 days (Table 7, Fig 7). LC_{50} values were 0.25 % for nano neem oil, 0.26 % for nano acorus oil and 0.10 % for nano imidacloprid, while conventional formulations recorded higher LC_{50} values of 0.35 %, 0.47 % and 0.35 %, respectively (Table 8).

Storage studies

Seed germination declined gradually with increasing storage period; however, germination remained above the minimum seed certification standard (80 %) in all treated seeds. Seeds treated with nano imidacloprid and imidacloprid recorded the highest germination (> 94 %), followed by nano neem oil (92 %), neem oil (90 %), nano acorus oil (88.67 %) and acorus oil (88 %).

Seedling vigour index also decreased during storage, but treated seeds maintained significantly higher vigour than untreated control. After five months of storage, the highest vigour index was recorded in nano imidacloprid (1590) followed by imidacloprid (1551), nano neem oil (1459), neem oil (1389), nano acorus oil (1258) and acorus oil (1245), compared with control (803).

No insect damage or weight loss was observed in rice seeds treated with nano formulations or their conventional counterparts during 5 months of storage. In contrast, untreated seeds recorded 12 % insect damage and 5.56 % weight loss, indicating effective protection of stored rice from *R. dominica* (Table 9).

Table 1. Contact toxicity of nano neem oil and neem oil against lesser grain borer, *Rhyzopertha dominica* adults

Treatment (%)	Per cent adult mortality (HAT)*			Treatment (%)	Per cent adult mortality (HAT)*		
	24 HAT	48 HAT	72 HAT		24 HAT	48 HAT	72 HAT
Nano neem oil at 0.6 %	100.00 (90.0) ^a	100.00 (90.0) ^a	100.0 (90.0) ^a	Neem oil at 1 %	73.33 (59.00) ^a	76.67 (61.22) ^a	83.33 (66.14) ^a
Nano neem oil at 0.5 %	63.33 (52.78) ^b	83.33 (66.14) ^b	100.00 (90.0) ^a	Neem oil at 0.5 %	56.67 (48.93) ^{ab}	63.33 (52.78) ^b	6.67 (54.78) ^b
Nano neem oil at 0.4 %	46.67 (43.08) ^c	73.33 (59.00) ^c	93.33 (77.0) ^b	Neem oil at 0.25 %	43.33 (40.78) ^{bc}	46.6 (42.99) ^c	53.33 (46.92) ^c
Nano neem oil at 0.3 %	43.33 (41.15) ^c	53.33 (46.92) ^d	73.33 (59.0) ^c	Neem oil at 0.1 %	33.33 (35.22) ^c	36.6 (37.22) ^c	43.33 (41.15) ^d
Nano neem oil at 0.15 %	16.67 (23.86) ^d	26.67 (31.00) ^e	50.00 (45.0) ^d	Neem oil at 0.05 %	13.33 (21.14) ^d	16.67 (23.86) ^d	26.67 (31.00) ^e
Untreated control	0.00 (0.91) ^e	0.00 (0.91) ^f	0.00 (0.91) ^e	Untreated control	0.00 (0.91) ^d	0.00 (0.91) ^e	0.00 (0.91) ^f
Sed	2.50	2.63	3.77	SEd	5.32	3.95	2.81
F value	283.91	271.37	163.97	F value	30.43	59.88	129.79

HAT: Hours after treatment; *Mean of four replications. Means followed by same letters are not significantly different by DMRT. Figures in parentheses are angular transformed values.

Table 2. Contact toxicity of nano Acorus oil and Acorus oil against lesser grain borer, *Rhyzopertha dominica* adults

Treatment (%)	Per cent adult mortality (HAT)*			Treatment (%)	Per cent adult mortality (HAT)*		
	24 HAT	48 HAT	72 HAT		24 HAT	48 HAT	72 HAT
Nano Acorus oil at 0.94 %	70.00 (62.22) ^a	80.00 (63.93) ^a	86.67 (90.00) ^a	Acorus oil at 1 %	66.67 (55.37) ^a	76.67 (61.22) ^a	83.33 (83.86) ^a
Nano Acorus oil at 0.47 %	50.00 (45.00) ^{ab}	60.00 (50.77) ^b	63.33 (83.86) ^b	Acorus oil at 0.5 %	46.67 (43.08) ^b	60.00 (50.85) ^b	66.67 (63.43) ^b
Nano Acorus oil at 0.24 %	30.00 (33.00) ^{bc}	40.00 (39.23) ^c	60.00 (72.29) ^b	Acorus oil at 0.25 %	46.67 (43.08) ^b	53.33 (46.92) ^{bc}	56.67 (65.85) ^c
Nano Acorus oil at 0.09 %	20.00 (26.07) ^{bc}	30.00 (33.00) ^c	50.00 (50.77) ^b	Acorus oil at 0.1 %	43.33 (41.07) ^b	43.33 (41.15) ^c	46.67 (52.78) ^d
Nano Acorus oil at 0.05 %	10.00 (18.43) ^c	13.33 (21.14) ^d	23.33 (26.57) ^c	Acorus oil at 0.05 %	10 (18.43) ^c	20.00 (26.57) ^d	23.33 (28.78) ^e
Untreated control	0.00 (0.91) ^c	0.00 (0.91) ^e	0.00 (0.91) ^d	Untreated control	0.00 (0.91) ^c	0.00 (0.91) ^e	0.00 (0.91) ^f
SEd	10.57	3.61	3.05	SEd	5.41	2.82	2.81
F value	8.11	75.78	119.91	F value	27.41	115.58	133.96

HAT: Hours after treatment; *Mean of four replications. Means followed by same letters are not significantly different by DMRT. Figures in parentheses are angular transformed values.

Table 3. Contact toxicity of nano imidacloprid and imidacloprid against lesser grain borer, *Rhyzopertha dominica* adults

Treatment (%)	Per cent adult mortality (HAT)*			Treatment (%)	Per cent adult mortality (HAT)*		
	24 HAT	48 HAT	72 HAT		24 HAT	48 HAT	72 HAT
Nano imidacloprid at 0.5 %	83.33 (70.07) ^a	100 (90.00) ^a	100 (90.00) ^a	Imidacloprid at 0.5 %	63.33 (52.78) ^a	73.33 (63.93) ^a	93.33 (66.14) ^a
Nano imidacloprid at 0.23 %	56.67 (48.85) ^b	86.67 (68.86) ^a	96.6 (83.86) ^a	Imidacloprid at 0.23 %	33.33 (35.22) ^{ab}	40.00 (39.15) ^b	76.67 (54.78) ^{ab}
Nano imidacloprid at 0.05 %	36.67 (37.22) ^c	53.33 (46.92) ^c	80.00 (63.43) ^b	Imidacloprid at 0.05 %	30.00 (33.21) ^{ab}	36.67 (37.14) ^b	63.33 (48.85) ^b
Nano imidacloprid at 0.03 %	16.67 (23.86) ^d	46.67 (43.08) ^c	53.33 (46.92) ^c	Imidacloprid at 0.03 %	26.67 (23.86) ^{abc}	33.33 (35.22) ^b	56.67 (43.08) ^b
Nano imidacloprid at 0.01 %	13.33 (21.14) ^d	23.33 (28.78) ^d	26.67 (31.00) ^d	Imidacloprid at 0.01 %	16.67 (21.14) ^{bc}	20.00 (25.37) ^{bc}	23.33 (28.87) ^c
Untreated control	0.00 (0.91) ^e	0.00 (0.91) ^e	0.00 (0.91) ^e	Untreated control	0.00 (0.91) ^c	0.00 (0.91) ^c	0.00 (0.91) ^d
SEd	6.46	2.56	4.62	SEd	2.60	9.32	7.35
F value	27.71	292.98	103.60	F value	85.09	9.68	26.97

HAT: Hours after treatment; *Mean of four replications. Means followed by same letters are not significantly different by DMRT. Figures in parentheses are angular transformed values

Table 4. Probit analysis (LC₅₀) of plant products and their nano formulations on adult mortality of lesser grain borer, *Rhyzopertha dominica*

Sl. No.	Treatment	LC ₅₀ value (%)	Regression equation	Chi square value	Slope	Fiducial limits	
						Upper	Lower
1.	Nano neem oil	0.16	Y=3.01+3.85x	15.51	3.85±0.38	0.23	0.04
2.	Neem oil	0.17	Y=0.85+1.12x	2.27	1.12±0.13	0.22	0.13
3.	Nano acorus oil	0.16	Y=0.96+1.16x	10.72	1.16±0.13	0.32	0.04
4.	Acorus oil	0.17	Y=0.89+1.15x	3.86	1.15±0.13	0.21	0.13
5.	Nano imidacloprid	0.02	Y=3.21+1.94x	3.93	1.94±0.18	0.03	0.01
6.	imidacloprid	0.03	Y=1.69+1.22x	8.96	1.22±0.11	0.06	0.01

*LC₅₀ was calculated at three days after treatment.

Table 5. Efficacy of nano neem oil and neem oil against adult mortality of lesser grain borer, *Rhyzopertha dominica*

Treatment (%)	Per cent adult mortality			Treatment (%)	Per cent adult mortality		
	7 DAT	10 DAT	15 DAT		7 DAT	10 DAT	15 DAT
Nano neem oil 0.6 %	100.00 (90.00) ^a	100.00 (90.00) ^a	100.00 (90.00) ^a	Neem oil 1 %	76.67 (61.22) ^a	96.67 (83.86) ^a	100.00 (90.0) ^a
Nano neem oil 0.5 %	80.00 (63.93) ^b	96.67 (83.86) ^{ab}	100.00 (90.00) ^a	Neem oil 0.7 %	63.33 (52.78) ^b	86.67 (68.86) ^b	100.00 (90.0) ^a
Nano neem oil 0.4 %	73.33 (59.00) ^b	93.33 (77.71) ^{cd}	100.00 (90.00) ^a	Neem oil 0.5 %	53.33 (46.92) ^c	90.00 (75.00) ^a	100.00 (90.00) ^a
Nano neem oil 0.3 %	60.00 (50.85) ^c	90.00 (71.56) ^c	100.00 (90.00) ^a	Neem oil 0.25 %	33.33 (35.22) ^d	90.00 (71.57) ^a	100.00 (90.00) ^a
Nano neem oil 0.2 %	40.00 (39.15) ^d	90.00 (71.56) ^c	100.00 (90.00) ^a	Neem oil 0.1 %	33.33 (35.22) ^d	86.67 (68.86) ^a	100.00 (90.00) ^a
Untreated control	0.00 (0.91) ^e	0.00 (0.91) ^e	0.00 (0.91) ^b	Untreated control	0.00 (0.91) ^e	0.00 (0.91) ^b	0.00 (0.91) ^b
SEd	3.93	5.01	0.00	SEd	2.62	6.17	0.00
F value	114.00	84.70		F value	129.09	47.94	

DAT: Days after treatment; * Mean of four replications. Means followed by same letters are not significantly different by DMRT. Figures in parentheses are angular transformed value.

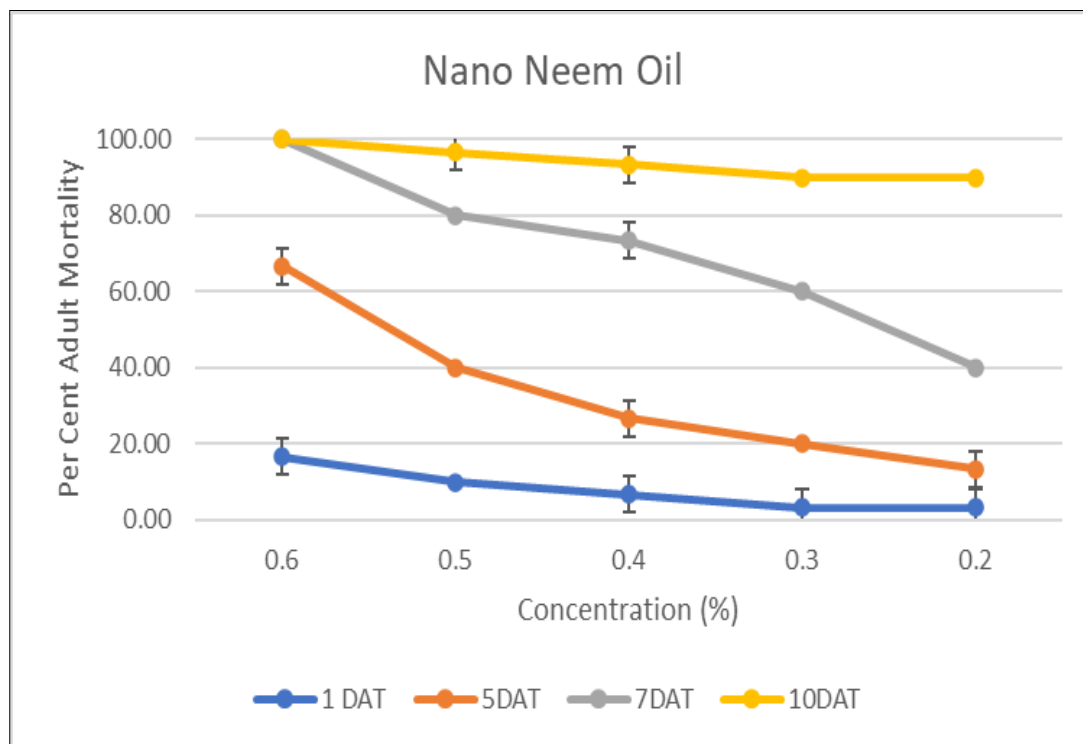


Fig. 5. Effect of nano neem oil on mortality of *Rhyzopertha dominica* at different time intervals.

Table 6. Efficacy of nano acorus oil and acorus oil against adult mortality of lesser grain borer, *Rhyzopertha dominica*

Treatment (%)	Per cent adult mortality			Treatment (%)	Per cent adult mortality		
	7 DAT	10 DAT	15 DAT		7 DAT	10 DAT	15 DAT
Nano acorus oil 1 %	76.67 (61.22) ^a	100.00 (90.00) ^a	100 (90.00) ^a	Acorus oil 1 %	63.33 (52.78) ^a	93.33 (77.71) ^a	100.00 (90.0) ^a
Nano acorus oil 0.5 %	56.67 (48.85) ^b	96.67 (83.86) ^a	100 (90.00) ^a	Acorus oil 0.5 %	53.33 (46.92) ^b	83.33 (66.14) ^b	100.00 (90.0) ^a
Nano acorus oil 0.25 %	40.00 (39.23) ^c	93.33 (81.14) ^{ab}	100 (90.00) ^a	Acorus oil 0.25 %	36.67 (37.22) ^c	76.67 (61.22) ^{ab}	96.67 (83.86) ^{ab}
Nano acorus oil 0.1 %	36.67 (37.14) ^{cd}	90.00 (75.00) ^{ab}	100 (90.0) ^a	Acorus oil 0.1 %	26.67 (31.00) ^d	73.33 (59.00) ^{bc}	93.33 (77.71) ^{bc}
Nano acorus oil 0.05 %	26.67 (31.00) ^d	80.00 (63.92) ^b	100 (90.0) ^a	Acorus oil 0.05 %	20.00 (26.57) ^d	66.67 (54.78) ^c	90.00 (77.57) ^c
Untreated control	0.00 (0.91) ^e	0.00 (0.91) ^c	0.00 (0.91) ^b	Untreated control	0.00 (0.91) ^e	0.00 (0.91) ^d	0.00 (0.91) ^d
SEd	3.11	8.08	3.54	SEd	2.36	4.43	5.07
F value	85.72	32.31	159.92	F value	120.79	73.35	92.51

DAT: Days after treatment; * Mean of four replications. Means followed by same letters are not significantly different by DMRT. Figures in parentheses are angular transformed values.

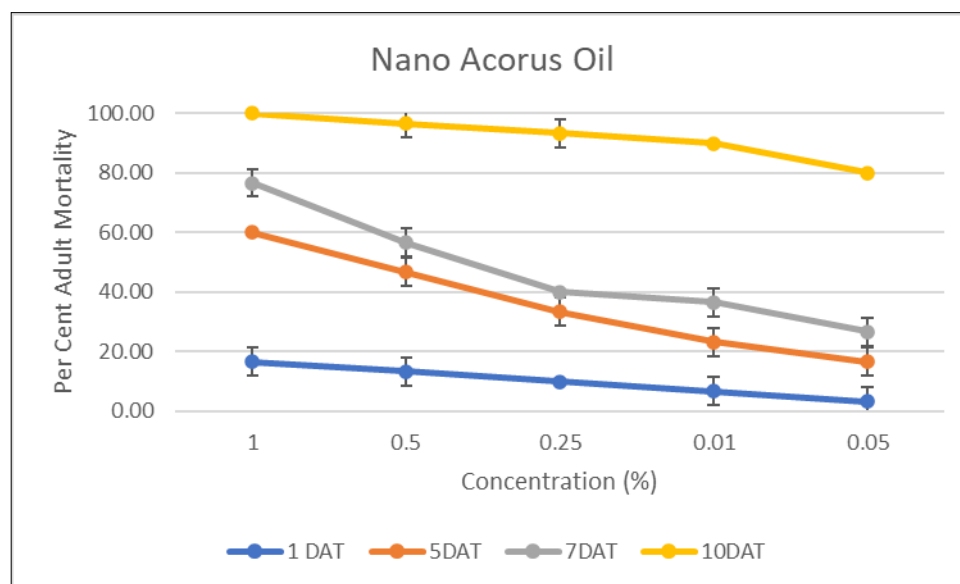
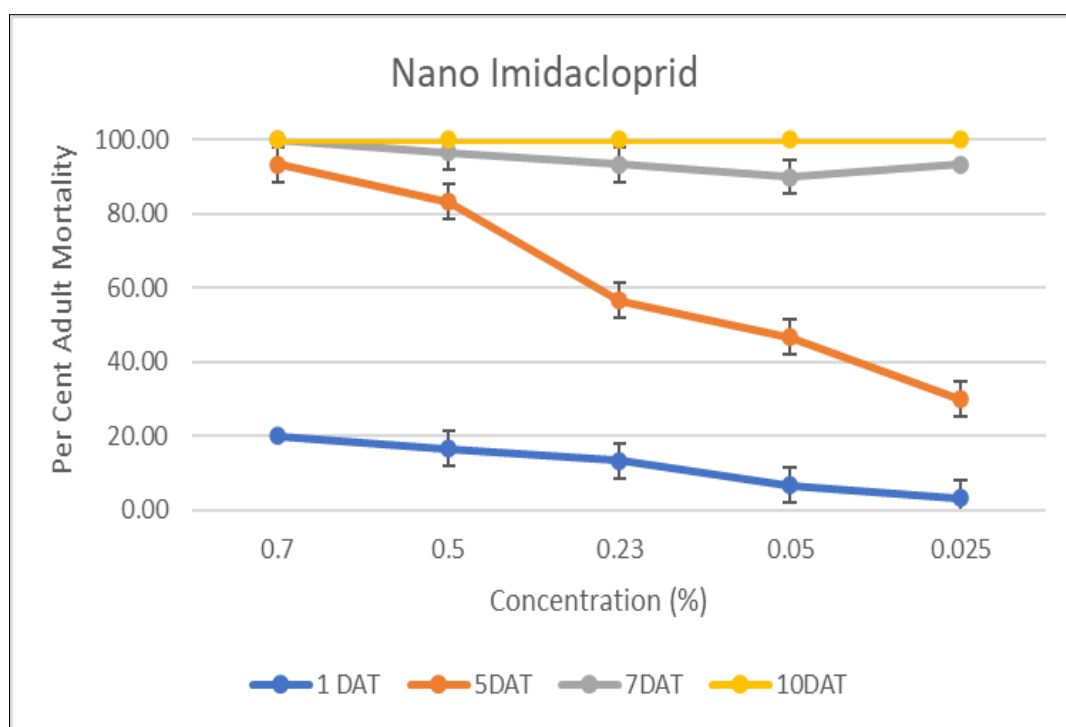


Fig. 6. Effect of nano acorus oil on mortality of *Rhyzopertha dominica* at different time intervals.

Table 7. Efficacy of nano imidacloprid and imidacloprid against adult mortality of lesser grain borer, *Rhyzopertha dominica*

Treatment (%)	Per cent adult mortality			Treatment (%)	Per cent adult mortality		
	7 DAT	10 DAT	15 DAT		7 DAT	10 DAT	15 DAT
Nano imidacloprid 0.7 %	100.00 (90.0) ^a	100.00 (90.0) ^a	100.00 (90.0) ^a	Imidacloprid 0.7 %	93.33 (77.71) ^a	100.00 (90.0) ^a	100.00 (90.0) ^a
Nano imidacloprid 0.5 %	96.67 (83.85) ^{ab}	100.00 (90.0) ^a	100.00 (90.0) ^a	Imidacloprid 0.5 %	83.33 (66.14) ^a	96.67 (83.85) ^a	100.00 (90.0) ^a
Nano imidacloprid 0.23 %	93.33 (77.71) ^{ab}	100.00 (90.0) ^a	100.00 (90.0) ^a	Imidacloprid 0.23 %	56.67 (48.84) ^b	83.33 (66.14) ^b	100.00 (90.0) ^a
Nano imidacloprid 0.05 %	93.33 (77.71) ^{ab}	100.00 (90.0) ^a	100.00 (90.0) ^a	Imidacloprid 0.05 %	46.67 (43.07) ^b	76.67 (61.11) ^b	100.00 (90.0) ^a
Nano imidacloprid 0.025 %	90.00 (71.56) ^b	100.00 (90.0) ^a	100.00 (90.0) ^a	Imidacloprid 0.025 %	30.00 (33.21) ^c	63.33 (52.77) ^c	100.00 (90.0) ^a
Untreated control	0.00 (0.91) ^c	0.00 (0.91) ^b	0.00 (0.91) ^b	Untreated control	0.00 (0.91) ^d	0.00 (0.91) ^d	0.00 (0.91) ^b
SEd	6.14	5.07	3.37	SEd	5.22	4.24	3.54
F value	58.81	86.59	175.50	F value	69.80	114.45	159.92

DAT: Days after treatment; * Mean of four replications. Means followed by same letters are not significantly different by DMRT. Figures in parentheses are angular transformed values.

**Fig. 7.** Effect of nano imidacloprid on mortality of *Rhyzopertha dominica* at different time intervals.**Table 8.** Probit analysis (LC₅₀) of plant products and their nano formulations on adult mortality of lesser grain borer, *Rhyzopertha dominica*

Sl. No.	Treatment	LC ₅₀ value	Fiducial limits		Regression equation	Chi square value	Intercept ± SE	Slope ± SE
			Upper	Lower				
1.	Nano neem oil	0.25	0.33	0.08	Y= 2.23 + 3.70x	14.43	2.23 ± 0.19	3.70 ± 0.39
2.	Neem oil	0.35	0.86	0.10	Y= 0.53 + 1.15x	9.10	0.53 ± 0.10	1.15 ± 0.17
3.	Nano Acorus oil	0.26	1.24	0.64	Y=0.96 +0.56x	6.15	0.96 ± 0.43	0.56 ± 0.10
4.	Acorus oil	0.47	3.80	0.22	Y= 0.56 + 0.87x	7.01	0.56 ± 0.10	0.87 ± 0.12
5.	*Nano imidacloprid	0.10	0.32	0.08	Y= 1.13 + 1.13x	19.48	1.13 ± 0.10	1.13 ± 0.11
6.	*Imidacloprid	0.35	1.89	0.16	Y= 0.47 + 1.05x	10.61	0.47 ± 0.10	1.05 ± 0.12

*LC₅₀ of nano imidacloprid and imidacloprid was calculated after 5 days. LC50 of other treatments were calculated after 7 days.

Table 9. Efficacy of plant products and nano formulations against lesser grain borer, *R.dominica* per cent damage, per cent weight loss in stored rice and other seed quality parameters

Treatments	Insect damage (%) *		Weight loss (%) *		Germination (%)*		Seedling vigour index I**	
	1M		5M		1M	5M	1M	5M
Imidacloprid	0.00 (4.05) ^b	0.00 (4.05) ^b	0.00 (4.05) ^b		100.00 (90.00) ^a	94.00 (76.16) ^{ab}	2450.00 (49.51) ^{ab}	1551.00 (39.39) ^a
Nano imidacloprid	0.00 (4.05) ^b	0.00 (4.05) ^b	0.00 (4.05) ^b		100.00 (90.00) ^a	96.00 (78.46) ^a	2531.67 (50.32) ^a	1590.00 (39.89) ^a
Neem oil	0.00 (4.05) ^b	0.00 (4.05) ^b	0.00 (4.05) ^b		97.33 (82.31) ^{ab}	90.00 (71.57) ^{abc}	2326.67 (48.24) ^{bc}	1389.00 (37.28) ^b
Nano neem oil	0.00 (4.05) ^b	0.00 (4.05) ^b	0.00 (4.05) ^b		98.67 (86.15) ^a	92.00 (73.86) ^{abc}	2394.07 (49.94) ^{ab}	1459.00 (38.21) ^b
Acorus oil	0.00 (4.05) ^b	0.00 (4.05) ^b	0.00 (4.05) ^b		97.33 (82.31) ^{ab}	88.00 (69.73) ^{cd}	2301.20 (47.98) ^{bc}	1245.00 (35.29) ^c
Nano Acorus	0.00 (4.05) ^b	0.00 (4.05) ^b	0.00 (4.05) ^b		97.33 (82.31) ^{ab}	88.67 (70.34) ^{cd}	2314.53 (48.12) ^{bc}	1258.00 (35.49) ^c
Untreated control	1.67 (7.33) ^a	12.00 (20.26) ^a	5.56 (13.45) ^a		93.33 (75.20) ^b	76.67 (61.12) ^d	2085.20 (45.67) ^d	803.00 (28.35) ^d
S.Em(±)	0.25	0.20	0.07		3.25	1.55	0.53	0.39
CD at 5 %	0.74	0.58	0.19		9.59	4.59	1.57	1.16

*Values in the parentheses are angular transformed values; ** Values in the parentheses are square root transformed values.

Discussion

The nano silica-encapsulated formulations developed in the present study produced particles within the nano meter range with stable zeta potential values, indicating successful nano-formulation with good dispersion stability. Reduced particle size increases the surface area and enhances the interaction of active compounds with the insect body, which may contribute to improved insecticidal activity. Nano emulsion systems are known to improve the stability and bioavailability of active compounds such as azadirachtin, thereby enhancing their biological efficacy against insect pests (25–27). In addition, reduced droplet size in nano emulsions has been associated with improved penetration and uptake of essential oil components by insects (28–30).

The bioassay results clearly demonstrated that nano silica-encapsulated formulations were more toxic to *R. dominica* than their conventional counterparts. Among the tested treatments, nano silica-encapsulated neem oil exhibited the highest efficacy, followed by nano silica-encapsulated acorus oil and showed comparable performance with the chemical check Imidacloprid. The enhanced toxicity of nano formulations may be attributed to better dispersion, increased surface area and improved penetration of active ingredients through the insect cuticle. Similar findings were reported where nano emulsion formulations of eucalyptus oil showed higher insecticidal activity than crude oil against *Sitophilus oryzae* and *Tribolium castaneum* infesting stored rice (31).

Surfactant concentration and droplet size are important factors influencing the insecticidal efficiency of nano formulations. Smaller droplet size improves solubility, mobility and dispersion of active compounds, which may result in enhanced toxicity (32). Previous studies have also reported that changes in surfactant concentration and formulation ratios can affect droplet size and toxicity of nano emulsions, leading to lower LC₅₀ values (33). Apart from the toxic effects of the essential oil components, silica-based particles may contribute to insect mortality by adsorbing cuticular lipids, thereby disrupting the protective cuticle barrier and causing desiccation (34).

The probit analysis further confirmed the higher potency of nano formulations, as evidenced by lower LC₅₀ values compared with conventional formulations against *R. dominica*. Enhanced

insecticidal activity of nano-encapsulated plant oils has been widely reported in stored-product pest management (35). Encapsulation of essential oils with nano silica significantly improved their insecticidal efficacy, which is consistent with earlier reports where nano emulsions of *Baccharis reticularia* essential oil exhibited strong repellent activity at concentrations of 4.4 g cm⁻² or higher (36). Similarly, nano-formulated azadirachtin showed improved insecticidal activity against *Culex quinquefasciatus* with mortality levels reaching 86.6 % (26).

The present findings on the efficacy of acorus oil and nano acorus oil against *R. dominica* in rice are in agreement with earlier studies where nano emulsions of *A. calamus* at 1 % concentration resulted in 90 % mortality of *Callosobruchus maculatus* within 24 hr., compared with 78.33 % mortality recorded with microscale emulsions at the same concentration (37).

Seed germination gradually declined with increasing storage duration across treatments. However, germination remained above the minimum seed certification standard (80 %) in all treated seeds compared with the untreated control. Seeds treated with nano imidacloprid maintained the highest germination percentage throughout the storage period, followed by nano neem oil and nano acorus oil. These findings suggest that nano bioformulations do not adversely affect seed viability during storage. Similar results were reported where castor nano emulsion effectively controlled *S. oryzae* without affecting wheat seed germination during storage (38). Earlier studies also indicated that plant oils such as neem, eucalyptus, sunflower and castor oil did not significantly affect pigeonpea seed germination during storage (39).

The effectiveness of neem-based formulations observed in the present study is supported by earlier reports demonstrating the long-term efficacy of neem treatments against *C. chinensis* in stored black gram for up to 15 months (40).

Seedling vigour index decreased gradually with increasing storage duration in all treatments. However, seeds treated with nano and conventional imidacloprid maintained relatively higher vigour than other treatments. Among the bioformulations, nano neem oil recorded the highest vigour index followed by nano acorus oil. The improved seedling vigour in treated seeds may be attributed to effective protection from insect infestation and maintenance of seed quality during storage.

No insect damage or weight loss was observed in rice seeds treated with nano bioformulations and their corresponding conventional formulations throughout the storage period. These treatments were comparable with the chemical check imidacloprid and nano imidacloprid, whereas the untreated control recorded considerable insect damage and grain weight loss. These findings indicate the potential of nano bioformulations for effective protection of stored grains. Similar studies have reported that nano-formulated essential oils effectively suppress infestation and reproduction of stored-product pests such as species of *Tribolium* under storage conditions (41–43).

Conclusion

The present study demonstrated that nano silica-encapsulated formulations of plant oils significantly enhanced insecticidal activity against *Rhyzopertha dominica* compared with conventional formulations. Among the tested treatments, nano silica-encapsulated neem oil exhibited the highest efficacy, followed by nano acorus oil and showed performance comparable to the chemical insecticide imidacloprid. The improved effectiveness of nano formulations can be attributed to reduced particle size, increased surface area and enhanced penetration of active compounds. Importantly, the nano bioformulations did not adversely affect seed germination or seedling vigour during storage and effectively prevented insect damage and grain weight loss. These findings highlight the potential of nano-encapsulated plant oils as eco-friendly alternatives to synthetic pesticides for the protection of stored rice. The developed nano bioformulations could therefore serve as sustainable pest management tools for improving grain storage and reducing post-harvest losses. Overall, the results demonstrate that nano silica encapsulated bioformulations can serve as effective and safer alternatives to conventional chemical insecticides and fumigants for the management of *R. dominica* in stored rice. Further studies on large-scale application and long-term storage conditions will help in developing these nano formulations as sustainable pest management tools for stored grain protection.

Acknowledgements

The authors sincerely acknowledge Acharya N. G. Ranga Agricultural University (ANGRAU) for providing the necessary facilities and support for conducting this research.

Authors' contributions

RM conceptualised the study, supervised the research work, contributed to data analysis and critically revised the manuscript. TNVKVP was responsible for the synthesis and characterisation of nano bioformulations and edited the manuscript. GSP contributed to data analysis and manuscript revision. AKV conducted the research work, prepared the manuscript, compiled and analysed the data and performed photography. RKS assisted with data analysis and manuscript revision. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

- Doherty EM, Camano-Flores N, Sun Q, Wilson BE. Examining factors influencing varietal resistance to *Rhyzopertha dominica* (F.) in stored rice. *Crop Prot.* 2025; 190:107087. <https://doi.org/10.1016/j.cropro.2024.107087>
- Adhikari V, Dabhi MV. Bionomics and morphometric study of *Rhyzopertha dominica* Fabricius on stored wheat. *J Exp Agric Int.* 2025;47(7):426–34. <https://doi.org/10.9734/jeai/2025/v47i73583>
- Obretenchev D, Zidan F, Atanasova D. Damage and weight losses of stored cereals caused by the lesser grain borer *Rhyzopertha dominica* F. (Coleoptera: Bostrichidae). *Agric Sci.* 2025;17(45). <https://doi.org/10.22620/agricsci.2025.45.004>
- Anu KV, Mandal R, Panduranga GS, Prasad TN. Management of lesser grain borer *Rhyzopertha dominica* using safer botanicals in stored rice. *J Exp Zool India.* 2024;27(1):1. <https://doi.org/10.51470/jez.2024.27.1.1151>
- Rajasri M, Rao PS. Neem formulations—safer seed protectants against pulse beetle *Callosobruchus chinensis* for long term storage of Bengal gram. *Int J Appl Biol Pharm Technol.* 2012;3(3):323–28.
- Nawrot J, Harmatha J. Natural products as antifeedants against stored product insects. *Post Harvest News Inf.* 1994; 5:17–21.
- Rajendran S, Sriranjini V. Plant products as fumigants for stored-product insect control. *J Stored Prod Res.* 2008;44(2):126–35. <https://doi.org/10.1016/j.jspr.2007.08.003>
- Isman MB. Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. *Annu Rev Entomol.* 2006;51:45–66. <https://doi.org/10.1146/annurev.ento.51.110104.151146>
- Koul O, Walia S, Dhaliwal GS. Essential oils as green pesticides: potential and constraints. *Biopestic Int.* 2008;4(1):63–84.
- Ranjith HV, Thakare VS, Arya PS, Bhoi TK, Subramanian S. Phosphine resistance: development, monitoring, strategies and alternatives for management in stored grain pests. *Int J Adv Biochem Res.* 2024;8(7):753–60. <https://doi.org/10.33545/26174693.2024.v8.i7Sj.1630>
- Alnajim I, Aldosary N, Agarwal M, Liu T, Du X, Ren Y. Role of lipids in phosphine resistant stored-grain insect pests *Tribolium castaneum* and *Rhyzopertha dominica*. *Insects.* 2022;13(9):798. <https://doi.org/10.3390/insects13090798>
- FAO. Manual of the prevention of post-harvest grain losses – fumigant issues and resistance concerns. Rome: FAO; 2024.
- Revathy VS, Jacob AM, Binu N. Insecticidal efficiency of selected essential oils against stored pests *Sitophilus oryzae* and *Callosobruchus maculatus* using GC-MS analysis. *Sci Rep.* 2025. <https://doi.org/10.1038/s41598-025-29149-1>
- Gharsan FN. Bioactivity of plant nanoemulsions against stored-product insects (order Coleoptera): a review. *J Entomol Sci.* 2024;59(4):355–65. <https://doi.org/10.18474/JES23-84>
- González JO, Gutiérrez MM, Ferrero AA, Band BF. Essential oils nano formulations for stored-product pest control—characterization and biological properties. *Chemosphere.* 2014; 100:130–38. <https://doi.org/10.1016/j.chemosphere.2013.11.056>

16. Rani KS, Rajasri M, Manjunath MM. Development of nano formulations of essential oils for stored grain pest management: a review. *J Pharm Innov.* 2023;12(6):871–78.
17. Ikawati S, Himawan T, Abadi AL, Tarno H. Toxicity nano insecticide based on clove essential oil against *Tribolium castaneum* (Herbst). *J Pestic Sci.* 2021;46(2):222–28. <https://doi.org/10.1584/jpestics.D20-059>
18. Omidian H, Cubeddu LX, Gill EJ. Harnessing nanotechnology to enhance essential oil applications. *Molecules.* 2025;30(3):520. <https://doi.org/10.3390/molecules30030520>
19. Sarmah K, Anbalagan T, Marimuthu M, Mariappan P, Angappan S, Vaithiyanathan S, et al. Innovative formulation strategies for botanical- and essential oil-based insecticides. *J Pest Sci.* 2025;98(1):1–30. <https://doi.org/10.1007/s10340-024-01846-2>
20. Tiwari S, Dubey NK. Nanoformulated essential oils against fungal and mycotoxin contamination of post-harvest commodities: a sustainable approach for food safety. *Indian J Nat Prod Resour.* 2025;16(1):13–28.
21. ISTA. International rules for seed testing. *Seed Sci Technol.* 1999;27(Suppl):25–30.
22. ISTA. International rules for seed testing. Bassersdorf: International Seed Testing Association; 2014.
23. Abdul-Baki AA, Anderson JD. Vigor determination in soybean seeds by multiple criteria. *Crop Sci.* 1973;13:630–33. <https://doi.org/10.2135/cropsci1973.0011183X001300060013x>
24. Snedecor GW, Cochran WG. Statistical methods. 6th ed. New Delhi: Iowa State College Press; 1967.
25. Choupanian M, Omar D, Basri M, Asib N. Preparation and characterization of neem oil nanoemulsion formulations against *Sitophilus oryzae* and *Tribolium castaneum* adults. *J Pest Sci.* 2017;42(4):158–65. <https://doi.org/10.1584/jpestics.D17-032>
26. Anjali CH, Sharma Y, Mukherjee A, Chandrasekaran N. Neem oil (*Azadirachta indica*) nanoemulsion—a potent larvicidal agent against *Culex quinquefasciatus*. *Pest Manag Sci.* 2012;68(2):158–63. <https://doi.org/10.1002/ps.2233>
27. Kumar RS, Shiny PJ, Anjali CH, Jerobin J, Goshen KM, Magdassi S. Distinctive effects of nano-sized permethrin in the environment. *Environ Sci Pollut Res.* 2013;20(4):2593–602. <https://doi.org/10.1007/s11356-012-1161-0>
28. Pavoni L, Benelli G, Maggi F, Bonacucina G. Green nanoemulsion interventions for biopesticide formulations. In: Rai M, Ribeiro C, editors. *Nano-biopesticides today and future perspectives*. London: Academic Press; 2019. p. 133–60. <https://doi.org/10.1016/B978-0-12-815829-6.00005-X>
29. Pascual-Villalobos MJ, Guirao P, Diaz-Banos FG, Canto-Tejero M, Villora G. Oil in water nanoemulsion formulations of botanical active substances. In: Rai M, Ribeiro C, editors. *Nano-biopesticides today and future perspectives*. London: Academic Press; 2019. p. 223–47. <https://doi.org/10.1016/B978-0-12-815829-6.00009-7>
30. Rani KS, Rajasri M, Panduranga G, Prasad TNKV. Phosphine resistance monitoring, molecular characterization and management of *Tribolium* spp. in stored rice. Master's thesis. Tirupati: Acharya N.G. Ranga Agricultural University; 2022.
31. Adak T, Nishant B, Patil NB, Govindharaj G, Gadratagi B, Annamalai M, et al. Nanoemulsion of eucalyptus oil: an alternative to synthetic pesticides against storage insects (*Sitophilus oryzae* and *Tribolium castaneum*) of rice. *Ind Crops Prod.* 2019;140:111659. <https://doi.org/10.1016/j.indcrop.2019.111849>
32. Sasson Y, Levy-Ruso G, Toledano O, Ishaaya I. Nanosuspensions: emerging novel agrochemical formulations. In: Ishaaya I, Nauen R, Horowitz AR, editors. *Insecticides design using advanced technologies*. Berlin: Springer; 2007. p. 1–39. https://doi.org/10.1007/978-3-540-46907-0_1
33. Dhivya V, Jeyarajan NS, Subramanian KS, Johnson TE, Rajamani K, Santhanakrishnan VP, et al. Development of *Acorus calamus* nanoemulsion and its insecticidal activity against pulse beetle (*Callosobruchus maculatus*). *Int J Agric Sci.* 2019;11(9):8387–90.
34. Barik TK, Sahu B, Swain V. Nano silica from medicine to pest control. *Parasitol Res.* 2008;103(2):253–58. <https://doi.org/10.1007/s00436-008-0975-7>
35. Lima AL, Paula S, Ferreira S, Manoel DN, Garcia J, Vera LP, et al. Nano-emulsions of the essential oil of *Baccharis reticularia* as eco-friendly repellents against *Tribolium castaneum*. *Ind Crops Prod.* 2021;162:113282. <https://doi.org/10.1016/j.indcrop.2021.113282>
36. Sabbour MMA. Efficacy of natural oils on the biological activity of *Callosobruchus maculatus* and *Callosobruchus chinensis*. *Bull Natl Res Cent.* 2019;43:206. <https://doi.org/10.1186/s42269-019-0252-1>
37. El-Naby A, Shima SI, Mahmoud FH, El-Habal NA, Abdou MS, Abdel-Rheim KH. Efficacy of prepared castor oil nanoemulsion formulation against rice weevil *Sitophilus oryzae*. *Egypt Sci J Pestic.* 2020;6(4):33–44.
38. Lal D, Raj DV. Efficacy of application of four vegetable oils as grain protectants against *Callosobruchus maculatus*. *Adv Biomed Res.* 2012;3(2):55–59.
39. Rajasri M, Sudharani M, Rao PS. Ecofriendly management of pulse beetle *Callosobruchus chinensis* using neem formulations in black gram. *Int J Sci Res.* 2014;3(11):2944–48.
40. Dhivya V, Jeyarajan NS, Subramanian KS, Johnson TE, Rajamani K, Santhanakrishnan VP, et al. Formulation of sweet flag oil (*Acorus calamus*) nano emulsion for the management of *Sitophilus oryzae*. *Int J Chem Stud.* 2019;7(3):2072–76.
41. Sabbour MM. Efficacy of nano-formulated essential oils on *Tribolium castaneum* and *Tribolium confusum*. *Bull Natl Res Cent.* 2020;44(1):111. <https://doi.org/10.1186/s42269-020-00336-6>
42. Kannan N, Chandrasekaran N. Targeting *Tribolium castaneum* with nano emulsified essential oils: a green approach to pest control. *J Stored Prod Res.* 2026;115:102829. <https://doi.org/10.1016/j.jspr.2025.102829>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc. See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.