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Insecticidal and repellent activities of TiO_2 encapsulated nanoparticles synthesized from *Salvia officinalis* against the cigarette beetle, *Lasioderma serricorne* (L.)

Nasira Parveen N, Deepa B, Dharani P, Elumalai K*
Department of Zoology, Unit of Entomotoxicity, Government Arts College (Autonomous), Nandanam, Chennai, Tamil Nadu, India
Corresponding Author: Elumalai K

Abstract

Lasioderma serricorne (cigarette beetle) is a harmful stored-product pest that causes significant economic damage globally. Traditional synthetic pesticides pose environmental and health hazards, highlighting the need for sustainable alternatives. This research investigates the insecticidal and repellent effects of green-synthesized titanium dioxide nanoparticles (TiO_2-NPs) using *Salvia officinalis* (sage) extracts against *L. serricorne*. Fresh sage leaves from southern India were powdered and wet-milled with TiO_2 in ethanol (1:10) to produce TiO_2-coated sage nanoparticles, which were then incubated at 80°C. Adult *L. serricorne* were reared under controlled conditions (21–49°C, 50% RH, 12-hour light cycle). The insecticidal and repellent activities were tested at five concentrations (10–50 ppm) over 24, 48, and 72 hours, with neem azal as a positive control. Mortality data were analyzed with probit analysis to determine LC_{50} and LC_{90} at 95% confidence. Results showed concentration- and time-dependent effectiveness, with 50 ppm causing 76.83% mortality at 24 hours, 82.41% at 48 hours, and 95.72% at 72 hours. LC_{50} values decreased from 34.400 ppm (24h) to 23.087 ppm (72h), and LC_{90} values from 62.052 ppm to 44.744 ppm over time. Repellent activity at 50 ppm increased from 86.1% at 24 hours to 97.2% at 72 hours. All treatments differed significantly from controls ($p < 0.05$, DMRT), with high regression coefficients ($R^2 = 0.986$–0.992). The green-synthesized TiO_2-coated sage nanoparticles exhibit strong insecticidal and repellent effects that increase with concentration and exposure time, as indicated by decreasing LC_{50} values, indicating sustained bioactivity. This eco-friendly nano biopesticide presents a promising alternative to synthetic chemicals for integrated pest management of stored products. Future studies should evaluate safety for non-target species, residual effects, and practical field applications to support commercialization.

Keywords: *Lasioderma serricorne*, titanium dioxide nanoparticles, *Salvia officinalis*, green synthesis, insecticidal activity, repellent activity, stored product pest, nanobiopesticide

Introduction

This investigation evaluates the entomotoxic and deterrent properties of titanium dioxide nanoparticles (TiO2-NPs) synthesized via a biogenic approach using *Salvia officinalis* extracts against *Lasioderma serricorne*, a pervasive stored-product pest. This approach leverages the growing interest in eco-friendly pest control methods and recognizes the potential of nanotechnology to provide novel insecticidal and repellent agents that mitigate the environmental and health concerns associated with conventional pesticides (Abbood *et al*., 2024) [1]. Specifically, this study will quantify the mortality rates, antifeedant effects, and repellency of the biosynthesized TiO_2 nanoparticles across various concentrations and exposure durations on adult and larval stages of *L. serricorne*, building upon previous research demonstrating the insecticidal efficacy of TiO_2 nanoparticles against other agricultural and household pests (Al-Numer & Mustafa, 2024; Gutiérrez-Ramírez *et al*., 2021; Ishaq *et al*., 2020) [4, 17, 21]. This includes studies that have explored the lethal effects of titanium oxide nanoparticles on pests such as *Periplaneta americana* via both contact and ingestion (Gutiérrez-Ramírez *et al*., 2021) [17].

Encapsulating TiO_2 in a natural extract such as *Salvia officinalis* could enhance stability and targeted delivery, potentially amplifying efficacy and reducing off-target effects. The inherent properties of these metal oxide nanoparticles, including physical, chemical, and biological attributes dictated by their dimensions and morphologies, make them promising candidates for integrated pest management strategies (Farooqi *et al*., 2024) [15]. This study focuses on *Lasioderma serricorne*, a coleopteran pest that infests a wide range of dried plant products and poses significant economic threats to stored goods (Rankić *et al*., 2021) [33]. Thus, this research will contribute to the development of sustainable pest management strategies by characterizing the insecticidal and repellent activities of TiO2 nanoparticles against this economically significant pest. This investigation seeks to delineate the specific mechanisms of action of these biosynthesized TiO2 nanoparticles, distinguishing between contact toxicity, ingestion toxicity, and repellent effects, and to assess their dose-response relationships and residual efficacy. Additionally, the study will explore the potential for synergistic effects from the combined action of TiO2 nanoparticles and bioactive compounds in *Salvia officinalis* extracts. This exploration into the synergistic potential of botanical extracts and nanomaterials aligns with the broader push towards sustainable agriculture and eco-friendly pest control, addressing limitations of conventional synthetic pesticides (Ansari *et al*., 2025; El-Bakry *et al*., 2025) [5]. Previous research has demonstrated the insecticidal effects of titanium dioxide nanoparticles against various insect species, including *Periplaneta Americana* (Gutiérrez-Ramírez *et al*., 2024; Silva & Miller, 2021) [19, 36] and *Tribolium castaneum* (Hilal *et al*., 2021) [20]. For instance, titanium dioxide nanoparticles have demonstrated high mortality rates in *Sitophilus oryzae*, *S. zeamais*, and *T.*

castaneum under both storage and laboratory conditions (Gupta *et al*., 2023) [16]. However, there remains a paucity of research specifically investigating the entomotoxic and repellent activities of green-synthesized TiO2 nanoparticles, particularly those derived from *S. officinalis*, against *L. serricorne*. This gap highlights the necessity for rigorous evaluation of such formulations, particularly concerning their efficacy, potential for broad-spectrum application, and environmental fate, to advance their integration into integrated pest management programs (Campos *et al*., 2018) [10]. Therefore, this study aims to bridge this knowledge gap by providing empirical data on the efficacy of *S. officinalis*-derived TiO_2 nanoparticles as a sustainable pest management tool against *L. serricorne*. This research will also encompass the characterization of the biosynthesized nanoparticles using techniques such as UV-Vis spectroscopy, dynamic light scattering, and transmission electron microscopy to ascertain their physicochemical properties, which are critical to understanding their interactions with biological systems (Martínez-Cisterna *et al*., 2026) [27]. Furthermore, the study will assess the impact of these nanoparticles on non-target organisms to ensure environmental safety and evaluate the broader ecological implications of their application.

Materials and Methods

1. Collection, Extraction, and Coating Process:

The fresh leaves of *Salvia officinalis* are harvested from southern India. They are then thoroughly washed under running water to eliminate dust, dirt, and other contaminants. The cleaned leaves are crushed into a coarse powder using a grinder. To reduce particle size from larger solids to a fine powder, a wet milling method is employed, producing particles with very small size variations. Additionally, nanosized particles (2-20 nm) are produced using a top-down approach, employing tungsten balls at a 1:10 ratio with titanium dioxide and *S. officinalis* powder. This mixture is dissolved in 10 ml of ethanol and stirred vigorously to produce an ethanol-based crude extract. The extract is milled for 30 minutes to 1 hour to ensure an even distribution of TiO_2 nanoparticles in *S. officinalis* and ethanol. Finally, the remaining solvent is evaporated by incubating the extract at 80°C, preserving the TiO_2 nanoparticles coated with *Salvia officinalis* extract (Najm *et al*., 2022; Pavela *et al*., 2017).

2. Rearing of *Lasioderma serricorne*

In the current investigation, infected coriander seeds and turmeric powder were employed to culture *L. serrricorne* at room temperature. Then it is added to the uninfected grains kept in a clear, airtight plastic container, which is well-ventilated by a muslin cloth covering. A 12-hour photoperiod was used in a climate chamber with controlled temperatures between 21 and 49 degrees Celsius and a 50% relative humidity. Freshly moulted insects were employed for the experiment.

3. Insecticidal activity of TiO2-coated *S. officinalis*

The insecticidal activity was evaluated against newly emerged adults of *L. serricorne.* The TiO_2-coated *S. officinalis* extract is dissolved in ethanol. Different concentrations (10, 20, 30, 40, and 50 ppm) were applied to Whatman No. 1 filter paper, which was then dried for 5 minutes. These filter papers were attached to the inner margin of the container lid subjected to treatment. Simultaneously, the control was treated with neem Azal. The formula outlined by Abbott (1925) was utilized to compute insect mortality (Lade (2017) [11]

$$POD = \frac{Ts - Cs}{Cs} X\,100$$

POD: Percentage of damage. Ts: Number of insects in treated sample. Cs: Number of insects in control

4. Repellent activity of TiO2-coated *S. officinalis*

A bioassay setup was prepared using six plastic boxes (8 cm × 5 cm), with five subjected to treatment and the remaining one used as a control. The lumen of each box was connected internally with a 12 cm tube. The insect chamber box was filled with ten pairs of unsexed adults, and concentrations of 10, 20, 30, 40, and 50 ppm were evaluated. The control was treated with neem azal. The experiment was performed in triplicate to obtain a concordance value. Lwande's approach was used to count the number of insects in the control and treated boxes after 24, 48, and 72 hours. The percent effective inhibition (EPI) was calculated using the following formula:

$$EPI = \frac{Nt - Nc}{Nt + Nc} X\,100$$

Where Nc is the number of insects in the control boxes, and Nt is the number of insects in the treated boxes.

Using SPSS, a probit analysis was conducted on the mean mortality data to determine LC_{50}, LC_{90}, and other parameters at a 95% confidence level, including upper and lower confidence limits, chi-square, slope, and additional statistics. A p-value of $< 0.05\%$ indicates statistical significance.

Result

The subsequent sections present the outcomes of the experimental investigations, including spectroscopic and microscopic analyses of the biosynthesized nanoparticles, as well as quantitative and qualitative data on their insecticidal and repellent activities against *L. serricorne*.

Table 1: Insecticidal activity of *S. officinalis* encapsulated with TiO_2-nanoparticles tested *against L. serricorne* at 24 hrs.

Concentrations	**Mortality (%)**	**Exposure period-24hrs**		**R^2 Linear**
		LC_{50}(LCL-UCL)	**LC_{90}(LCL-UCL)**	
10ppm	12.47 ± 2.65^a	34.400 (32.888-38.194)	62.052 (56.695-69.656)	0.992
20ppm	23.09 ± 1.92^b			
30ppm	35.57 ± 1.59^b			
40ppm	60.14 ± 0.45^c			
50ppm	76.83 ± 1.83^c			
Neem azal	100.0 ± 0.00^d			

Values expressed are mean mortality ± standard deviations of three replications (n=20). Different alphabet in the column is statistically significant at $p<0.05\%$; DMRT.

Table 2: Insecticidal activity of *S. officinalis* encapsulated with TiO$_2$-nanoparticles tested *against L. serricorne* at 48 hrs.

Concentrations	Mortality (%)	Exposure period-48hrs		R^2 Linear
		LC$_{50}$ (LCL-UCL)	LC$_{90}$ (LCL-UCL)	
10ppm	18.20±2.07 ^{a}	30.599 (28.039-33.197)	57.928 (52.915-65.017)	0.986
20ppm	31.63±1.71 ^{a}			
30ppm	43.05 ±0.63^{b}			
40ppm	69.79±1.92 ^{c}			
50ppm	82.41± 0.74 ^{c}			
Neem azal	100.0±0.00 ^{d}			

Values expressed are mean mortality ± standard deviations of three replications (n=20). Different alphabet in the column is statistically significant at $p<0.05\%$; DMRT.

Table 3: Insecticidal activity of *S. officinalis* encapsulated with TiO$_2$-nanoparticles tested *against L. serricorne* at 72 hrs.

Concentrations	Mortality (%)	Exposure period-72hrs		R^2 Linear
		LC$_{50}$(LCL-UCL)	LC$_{90}$(LCL-UCL)	
10ppm	22.79±1.68 ^{a}	23.087 (20.711-25.237)	44.744 (41.488-49.049)	0.990
20ppm	40.88±1.04 ^{b}			
30ppm	60.51±0.77 ^{b}			
40ppm	81.11±1.25 ^{c}			
50ppm	95.72±0.45 ^{d}			
Neem azal	100.0±0.00 ^{d}			

Values expressed are mean mortality ± standard deviations of three replications (n=20). Different alphabet in the column is statistically significant at $p<0.05\%$; DMRT.

The insecticidal activity of TiO$_2$-coated *S. officinalis* was tested against the adult beetles of *L. serricorne,* and the data from the experiments are shown in Tables 1-3. It was analyzed that 34.400% and 62.052% were at 50% and 90% of the lethal concentration in 24hrs. In the same trend, the 50% and 90% lethal concentrations over a 48-hour duration were 30.599% and 57.928%, respectively. Similarly, the maximum mortality of 23.087% and 44.744% was noted for a 72-hour duration time at the concentration of 10, 20, 30, 40 and 50 ppm, respectively. The mortality of beetles is directly proportional to their exposure periods (hrs) to the concentrations of the TiO2-coated *S. officinalis*. As well as concentration, plays a greater role in increasing mortality, showing a trend similar to the duration of treatments.

Table 4: Repellent activity of *S. officinalis* encapsulated with TiO$_2$-nanoparticles tested *against L. serricorne* at varying test periods.

Concentrations	Exposure periods (in Hrs)		
	24 Hrs	48Hrs	72Hrs
10ppm	17.8±1.45^{a}	22.9±2.45^{a}	39.0±1.15^{a}
20ppm	34.0±0.85^{a}	47.4±1.32^{a}	54.6±0.82^{a}
30ppm	46.3±0.10^{b}	58.2±1.20^{b}	68.3±0.99^{b}
40ppm	62.8±0.80^{c}	76.0±1.14^{b}	83.0±0.78^{c}
50ppm	86.1±0.65^{c}	90.8±1.05^{c}	97.2±0.81^{d}
Neem azal	100.0±0.00 ^{d}	100.0±0.00 ^{d}	100.0±0.00 ^{d}

Values expressed are mean mortality ± standard deviations of three replications (n=20). Different alphabet in the column is statistically significant at $p<0.05\%$; DMRT.

The repellent effect of TiO2-coated S. officinalis was tested against adult L. serricorne beetles, with results shown in Table 4. After 24 hours, repellent effects were 17.8%, 34.0%, 46.0%, 62.8%, and 86.1% at 10, 20, 30, 40, and 50 ppm, respectively. After 48 hours, these increased to 22.9%, 47.4%, 58.2%, 76.0%, and 90.8% at the same concentrations. By 72 hours, the highest activity recorded was 39.0%, 54.6%, 68.3%, 83.0%, and 97.0% for each concentration. It is clear that, as temperature (27±2°C) and exposure time lengthened, L. serricorne showed maximum repellent activity.

Discussion

The observed repellent and insecticidal efficacy of TiO2-coated *S. officinalis* against *L. serricorne* aligns with previous research indicating that this pest is susceptible to various natural compounds and physical interventions (Naveena *et al*., 2021) [28]. For instance, studies have shown that *L. serricorne* exhibits significant behavioral responses to essential oils and plant extracts, demonstrating both repellent and insecticidal effects that vary with concentration and exposure duration (Lü & Liu, 2016; Lyu *et al*., 2018) [25, 26]. For example, essential oils from plants like *Mentha piperita* and *S. officinalis* have demonstrated contact toxicity against *Plodia interpunctella* larvae, with LC$_{50}$ values of 39.3 µl/L air and 30.3 µl/L air, respectively, after 72 hours of exposure, highlighting the dose-dependent nature of their efficacy (Allahvaisi *et al*., 2017) [3]. Furthermore, similar dose-dependent repellent effects have been observed with extracts from *Datura stramonium* and *Syzygium aromaticum* against *Trogoderma granarium*, where higher concentrations led to greater repellency (Umair *et al*., 2020) [38], and with *Ocimum basilicum* against *L. serricorne*, exhibiting a concentration-dependent increase in repellency over time (Naveen *et al*., 2021) [28]. This is further corroborated by studies on *Ligusticum pteridophyllum* essential oil and its main component, myristicin, which also demonstrated good repellent activities (Leite *et al*., 2023) [24].

Specifically, α-terpineol and terpinen-4-ol have been identified as highly effective repellents against adult L. serricorne, with the latter showing repellency comparable to

DEET at certain concentrations and exposure times (Zhang *et al*., 2015, 2016) [40, 41]. Similarly, essential oils from *Zingiber officinale* have shown high repellency against *T. castaneum* even at low concentrations, reaching 85% at 1.6 μL/L of air, and *Artemisia vulgaris* essential oil exhibited 100% mortality in *T. castaneum* at 8.0 μg/mL (Мартынов *et al*., 2019). Additionally, studies have demonstrated that extracts from plants such as *Parthenium hysterophorus* and *Vitex jatmansi* exhibit considerable repellent effects on adult *L. serricorne* within 48 hours (Latif, 2023) [23]. These findings are consistent with research on various plant essential oils, including eucalyptus, basil, and grapefruit, which have also demonstrated significant repellent effects against *L. serricorne* adults (Ren *et al*., 2022) [34]. These repellent properties are often attributed to volatile monoterpenes and sesquiterpenes, which act on the olfactory receptors of phytophagous insects, with compounds like 1,8-cineole, terpineol, and α-pinene being particularly effective (Bett *et al*., 2017) [9]. Such compounds are frequently used in commercial botanical insecticides, exploiting their rapid action via both contact and fumigation to enhance insecticidal efficacy (Bett *et al*., 2015; Pavela, 2016) [8, 31]. However, the efficacy of these botanicals can be highly species- and chemical-composition dependent, with certain essential oil combinations not necessarily improving insecticidal outcomes (Chaieb *et al*., 2017) [11]. The complex interactions between essential oil components and insect chemoreceptors can lead to varied responses, including instances in which certain plant essential oils may act as attractants rather than repellents at specific concentrations (Bedini *et al*., 2024) [7]. This underscores the necessity of comprehensive screening and validation of plant-derived compounds to optimize their use as effective, reliable pest management agents (Yadav *et al*., 2024) [39]. This nuanced understanding of botanical insecticide mechanisms and their species-specific effects is crucial for developing targeted pest control strategies that minimize off-target impacts and resistance development, particularly given that essential oils are generally regarded as safe for humans and the environment and represent an eco-friendly alternative to synthetic chemical insecticides (Rizvi *et al*., 2025) [37]. The biodegradability of these botanical compounds further mitigates environmental and health risks, while their diverse modes of action may delay the evolution of pest resistance, a common challenge with conventional pesticides (Kostić *et al*., 2022) [22]. Indeed, the multifaceted nature of botanical insecticides, encompassing repellent, antifeedant, and toxicant properties derived from non-host plants, positions them as a promising and sustainable alternative to synthetic chemical pesticides for pest management (Arokiyaraj *et al*., 2022) [6]. This aligns with the broader recognition of botanical insecticides as viable alternatives to synthetic compounds due to their rapid decomposition, minimal environmental burden, and the reduced likelihood of resistance development afforded by their multi-component nature (Ahmed *et al*., 2021; Pavela *et al*., 2023) [2, 32]. Moreover, the efficacy of botanical insecticides, including those based on essential oils, is well documented in reducing insect populations and mitigating agricultural damage, while posing fewer risks to non-target organisms and ecosystems than conventional chemical pesticides (Divekar, 2023; Tarasing *et al*., 2025) [13, 37].

Conclusion

The results of this study suggest that the fumigant and repellent effects of TiO2-coated *S. officinalis* can significantly affect the biological parameters of the cowpea insect pest *L. serricorne*, supporting the utility of plant-derived essential oils as effective bioinsecticides for stored-product pest management. These natural products offer several advantages, including relatively low cost, availability, and safety for pollinators and non-target organisms, making them environmentally friendly pest management options. The potential for developing these compounds as novel fumigants is substantial, given their lower mammalian toxicity and reduced environmental impact compared to conventional fumigants. Consequently, ongoing research extensively investigates essential oils and their major components as promising candidates for developing new insecticides, emphasizing their low mammalian toxicity, environmental persistence, and reduced potential for insect resistance. This focus on essential oils is further motivated by their capacity to affect both the physiological and behavioral aspects of pests, exhibiting insecticidal, repellent, and antifeedant properties. For instance, the complex chemical composition of many essential oils, often involving synergistic interactions among their constituents, contributes to their broad-spectrum activity and multifactorial modes of action against insects.

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