



PLANT-DERIVED NANO-EMULSION FOR STORED GRAIN INSECT MANAGEMENT

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Abstract

Essential oil-based nanoemulsions generated from plants provide an effective bio-insecticidal approach for controlling stored grain insect pests. Nano-emulsification improves the physicochemical stability, dispersion, and longevity of volatile essential oil components, leading to enhanced contact and fumigant toxicity. The nanoscale droplet size facilitates optimal grain surface covering, improved cuticular penetration, and prolonged release of bioactive chemicals, resulting in efficient disruption of insect neurological and respiratory systems. These formulations attain significant insect lethality at lower doses, while reducing residue buildup and non-target impacts. Consequently, essential oil nanoemulsions provide an ecologically benign and efficient substitute for synthetic pesticides in the sustainable protection of stored grains.

Keywords: Essential oil, nanoemulsion, stored grain insect

Introduction

Agriculture is pivotal to global food security; nevertheless, its ability to support a population anticipated to reach 9.3 billion by 2050 (Baliyarsingh & Pradhan, 2023) is increasingly limited by post-harvest losses and the need for better pest control measures. Insect pests inflict significant harm during storage,

resulting in about 14% of yearly worldwide food production losses (Pimentel, 2009), therefore diminishing grain quality, marketability, and appropriateness for human consumption. Essential oils (EOs) have arisen as sustainable substitutes for manufactured fumigants owing to their biodegradability and extensive bioactivity. Their insecticidal effectiveness stems from intricate combinations of terpenoids, aldehydes, alcohols, ketones, and alkaloids that function *via* several, synergistic ways. At the neurological level, EO components inhibit acetylcholinesterase and disrupt octopaminergic and GABA-gated chloride channel transmission, leading to neuromuscular dysfunction and death (Sakthiyavathi et al., 2025). These compounds concurrently disrupt metabolic homeostasis by inhibiting detoxification enzymes such as cytochrome P450 monooxygenases, glutathione S-transferases, and esterases, while also impairing mitochondrial respiration, resulting in ATP depletion, growth inhibition, diminished fecundity, and developmental failure. EO-derived compounds function as toxicants, repellents, feeding deterrents, growth inhibitors, sterilants, or attractants. Their integration into stored grains as oils or plant-derived materials effectively suppresses oviposition, restricts population establishment, and reduces post-harvest losses, underscoring their potential for sustainable pest management in stored products.

Stored grain insect pests: a major concern

For India's food security, reducing post-harvest losses from pest infestation is just as important as raising primary agricultural output. With insect-mediated losses estimated at 20–25% in India (Singh et al., 2021), despite the record food grain output of 3296.87 lakh tons in 2022–2023, substantial amounts are lost during storage, compared to 5–10% in temperate and 20–30% in tropical countries worldwide. Stored-grain insects, which are primarily coleopterans, are divided into two categories: primary pests (*Trogoderma granarium*, *Sitophilus oryzae*, and *Rhyzopertha dominica*), which infest intact kernels, and secondary pests (*Tribolium castaneum* and *Oryzaephilus surinamensis*), which colonize damaged grains. Together, these pests cause quantitative losses and qualitative deterioration that jeopardize food safety and market value. In developing nations like India, inadequate on-farm storage infrastructure increases the pressure of infestations, forcing farmers to sell their grain too soon and incurring financial losses. This underscores the pressing need for technically sound, scalable, and sustainable stored-grain pest management.

Challenges associated with chemical insect control

Since the escalation of chemical agriculture, synthetic pesticides have been fundamental to stored-product pest control owing to their swift efficacy, cost-effectiveness, and ease of application. Control techniques in stored-grain systems mostly depend on fumigants and residual contact insecticides. Fumigants like phosphine and methyl bromide are utilized in sealed environments to swiftly reduce populations via respiratory inhibition, while contact insecticides, primarily organophosphates and synthetic pyrethroids, are applied to grains or storage facilities for residual

protection. Nevertheless, extensive and indiscriminate use of these chemicals has led to many disadvantages, including disturbance of storage ecosystem equilibrium, pesticide residues in food products, threats to non-target creatures, and the pervasive development of resistance. In India, phosphine is the sole registered fumigant, and its recurrent misuse has resulted in resistant populations of significant storage pests (Rajashekar et al., 2025), while the ongoing use of malathion and deltamethrin has likewise induced resistance through metabolic detoxification and target-site insensitivity. The constraints have heightened the demand for advanced alternatives with reduced environmental impacts and enhanced effectiveness, such as nanoemulsion-based formulations, which improve bioavailability, stability, and targeted delivery of active compounds while minimizing dosage needs, environmental persistence, and non-target toxicity, thus presenting a promising, sustainable strategy for managing pests in stored grain.

Plant-derived nano-emulsions: a new approach

The manufacture of metallic nanoparticles by plants entails the bio-reduction of metal ions, with stability provided by phytochemicals including phenolics, flavonoids, alkaloids, terpenoids, sugars, and proteins, which serve as reducing and capping agents. The dimensions, shape, and surface chemistry of nanoparticles are influenced by the phytochemical composition of the extract and the polarity of the solvent; for instance, alcoholic extracts promote polyhedral structures, whereas aqueous extracts produce anisotropic forms (Montes et al., 2011). Physicochemical examination by UV–Vis, FTIR, XRD, DLS, SEM, and TEM validates the formation, crystallinity, and stability of nanoparticles (Kar et al., 2025).

Insect management with phytochemical-based nanoemulsions as foliar sprays increases the bioavailability, stability, and controlled release of active compounds, hence enhancing leaf coverage, cuticular penetration, and field effectiveness at reduced dosages. The amalgamation of green synthesis, comprehensive characterisation, and field validation underscores foliar nanoemulsions as ecologically friendly and very efficient solutions for insect pest control.

Mode of action

Nano-emulsions of essential oils (EOs) improve insecticidal effectiveness by enhancing stability, bioavailability, and targeted delivery of active constituents. Their nanoscale droplets guarantee homogeneous distribution, robust cuticular adherence, and rapid penetration through insect cuticles and spiracles. Upon internalization, EO constituents elicit multi-target toxicity by inhibiting acetylcholinesterase, modulating GABA-gated chloride channels and octopaminergic signalling, suppressing detoxification enzymes, and disrupting mitochondrial respiration, resulting in ATP depletion, oxidative stress, paralysis, and mortality. The regulated release and extended duration of nano-emulsions provide efficient pest control at lower dosages with minimum ecological consequences.

Key Mechanisms:

- i. **Enhanced delivery & penetration:** Nano-droplets improve cuticular adhesion, spiracular entry, and transcuticular diffusion of EO actives.
- ii. **Neurotoxicity:** Inhibition of acetylcholinesterase and interference with GABA and octopamine receptors cause neuromuscular dysfunction and paralysis.
- iii. **Metabolic disruption:** Impairment of midgut enzymes, mitochondrial

respiration, and induction of oxidative stress lead to ATP depletion.

- iv. **Anti-detoxification effects:** Suppression of cytochrome P450s, esterases, and GSTs reduces insect detoxification capacity.
- v. **Antifeedant and repellent action:** Volatile EO components deter feeding and oviposition, limiting infestation establishment.
- vi. **Prolonged efficacy:** Controlled release and improved stability enhance persistence while lowering application rates and environmental footprint

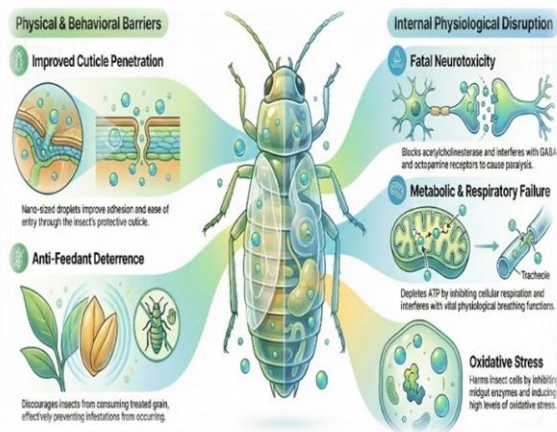


Figure 1: Mode of action of nano emulsion as Insecticide

Case Studies

Miloudi et al. (2024) reported that essential oils from *Satureja calamintha*, *Mentha piperita*, and *Chenopodium ambrosioides* showed insecticidal activity against *Tribolium confusum*, with individual and combined EOs exhibiting 28.8–72% repellency. Notably, a nanoemulsified ternary EO formulation applied at 1000 ppm achieved 100% adult mortality within four days on treated wheat, highlighting the superior efficacy of nanoemulsion-based EO delivery for stored-grain pest control.

Gharsan et al. (2022) reported that citronella essential oil, rich in citronellal (46.95%), citronellol (9.49%), linalool (9.46%), and β -caryophyllene (8.39%), and formulated as a ~58 nm nanoemulsion, exhibited markedly enhanced toxicity against *Oryzaephilus surinamensis*. The nanoemulsion significantly reduced LC_{50} values for adults (15.7–20.3 $\mu\text{L L}^{-1}$ for males and females) compared with the bulk essential oil (40.02–52.5 $\mu\text{L L}^{-1}$), demonstrating the superior insecticidal efficacy of nanoemulsion-based EO delivery systems for stored-grain pest control.

Abd El-Salam et al. (2024) demonstrated that nanoemulsions formulated with turmeric, sesame, and frankincense oils exhibited strong insecticidal activity against *Sitophilus oryzae*. Notably, the turmeric oil nanoemulsion achieved 100% adult mortality at 2000 $\mu\text{L kg}^{-1}$ within two weeks and completely suppressed progeny emergence over nine months, while sesame and frankincense nanoemulsions caused 90% and 83.33% mortality, respectively, underscoring the high efficacy and long-term protective potential of plant oil-based nanoemulsions for stored-grain pest management.

Conclusion

The widespread use of hazardous chemosynthetic pesticides has increased due to the aim to boost agricultural output and reduce food losses brought on by insects during post-harvest storage periods. But its contamination in the environment and increased health concerns to humans and domestic animals have changed the focus of acquiring environmentally friendly insecticides derived from living things. The use of nanotechnology in agriculture has gained popularity and shown promise. Plants are the preferred option for investigating active ingredients due to their diversity and the presence of many insect-specific bioactive

substances & nanoscience has made it easier to create efficient nano-biopesticides.

References

1. Abd El Salam, K. M., Abou El-Soud, G. M., Abd El Salam, M. M., Abd El-Naby, S. S., Abdel-Rheim, K. H., Lamlom, S. F., & Abdel-Megeed, A. (2024). Natural nanoemulsions: A sustainable solution for rice weevil control in stored paddy rice. *Journal of Stored Products Research*, 109, 102451.
2. Baliyarsingh, B., & Pradhan, C. K. (2023). Prospects of plant-derived metallic nanopesticides against storage pests-A review. *Journal of Agriculture and Food Research*, 14, 100687.
3. Gharsan, F. N., Kamel, W. M., Alghamdi, T. S., Alghamdi, A. A., Althagafi, A. O., Aljassim, F. J., & Al-Ghamdi, S. N. (2022). Toxicity of citronella essential oil and its nanoemulsion against the sawtoothed grain beetle *Oryzaephilus surinamensis* (Coleoptera: Silvanidae). *Industrial Crops and Products*, 184, 115024
4. Kar, A. K., Shraogi, N., Saji, J., Verma, R., Singh, D., Singh, A., & Patnaik, S. (2025). Comparative study on green versus chemical synthesis for metallic NPs with respect to physicochemical characterization and toxicity. *Next Materials*, 9, 101184.
5. Miloudi, S., Soulaïmani, B., Abbad, I., Abbad, A., & El Mouden, E. H. (2024). Potential of three selected plant essential oils and their synergistic combinations in management of *Tribolium confusum* on wheat grains. *Journal of Stored Products Research*, 109, 102464.

6. Montes, M. O., Mayoral, A., Deepak, F. L., Parsons, J. G., Jose-Yacamán, M., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2011). Anisotropic gold nanoparticles and gold plates biosynthesis using alfalfa extracts. *Journal of Nanoparticle Research*, 13(8), 3113-3121.
7. Pimentel, D. (2009). Pesticides and pest control. In *Integrated pest management: innovation-development process: volume 1* (pp. 83-87). Dordrecht: Springer Netherlands.
8. Rajashekar, Y., Devaraja, A., Thirumalesh, B. V., & Babu, C. S. V. (2025). Botanical insecticides for stored grain protection: Emerging challenges and future prospects. *Food Bioscience*, 107337.
9. Sakthiyavathi, S. S. K., Malaisamy, K., Kamalakannan, M., Murugesan, V., Palanisamy, S. R., Theerthagiri, A., & Kasivelu, G. (2025). Eco-nanotechnology: phyto essential oil-based pest control for stored products. *Environmental Science: Nano*, 12(9), 4150-4180.
10. Singh, K. D., Mobolade, A. J., Bharali, R., Sahoo, D., & Rajashekar, Y. (2021). Main plant volatiles as stored grain pest management approach: A review. *Journal of Agriculture and Food Research*, 4, 100127.