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Original Research Paper

Formulation and Field Efficacy of Nano-Emulsified Insecticides for Sustainable Pest Control in Cotton Against *Helicoverpa Armigera*

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Key Words

Nanoemulsion, *Helicoverpa Armigera*, Sustainable pest management, Cotton, Bio efficacy.

Abstract

The traditional pesticidal compounds have severe constraints such as low solubility, environmental persistence, and non-target toxicity. This paper examined the formulation of nano-emulsified lambda-cyhalothrin and efficacy against *Helicoverpa Armigera* (Hubner) infesting cotton (*Gossypium hirsutum L.*) using this formulation. Mean particle size of 126 ± 12 nm and zeta potential of -34.2 mV were obtained by using ultrasonication (20 kHz, 15 min) as the surfactants: Tween 80 and Span 20, to prepare nano-emulsion. Field experiments were carried out at Research Farm, CCS HAU Hisar, in kharif 2022 and 2023, which compared 5 treatments: nano-emulsion at 10,15, and 20 g a.i./ha; commercial EC formulation at 20 g a.i./ha; and no treatment. Three replications of the randomized complete block design were adopted. At 20 g a.i./ha, 89.3% larval kill at 7 days after treatment was achieved in nano-emulsion, which was considerably higher than that of the EC formulation (76.8%). Average boll damage was decreased to 8.4%. in comparison to 15.2 %. using EC formulation with 22.7%. Higher seed cotton (2,847 kg/ha). The nano-formulation was found to have better foliar adhesion, rainfastness, and UV stability. The cost-benefit analysis provided more returns of 18420/ha. Findings demonstrate that nano-emulsification is an effective approach to minimizing pesticide dosage without reducing efficacy, which fits the sustainable crop protection agenda.

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Introduction

Lepidopteran pests, especially *Helicoverpa Armigera* (Hubner), severely affect cotton growth, leading to a loss of up to 50 % of the yield every year (Khyade, 2018; Ahmad et al., 2020; Kranthi et al., 2001; Jadhav et al., 2025). Synthetic pyrethroids have continued to be the main option of control, but classic emulsifiable concentrate (EC) preparations have the drawbacks of being poorly water-soluble, rapidly photodegraded, and undergoing significant off-target migration (Muñoz-Bautista et al., 2025). Such restrictions require higher application rates, which worsens the situation with environmental pollution and the emergence of insecticide resistance (Naranjo, 2021). The inactive delivery systems used in the delivery of pesticides are also shown by the fact that less than 0.1 % of implemented pesticides are taken by the target pests, as estimated by the Food and Agriculture Organization (Jepson et al., 2020).

Nanotechnology also presents revolutionary approaches by offering nano-emulsified types of delivery systems with particle sizes of less than 200 nm (Patel & Joshi, 2022). These types of formulations offer increased solubility, greater foliar penetration, control kinetics of release, and better stability to environmental degradation (Kah et al., 2018). Recent investigations indicate that the nano-emulsified insecticides have 3-5 times greater bioavailability than traditional formulations Li et al., 2021; Liang et al., 2020). Their commercial adoption is, however, limited by the field validation that is limited in a variety of agro-climatic conditions (Jena et al., 2025). Although technical feasibility is established by laboratory procedures, there are glaring gaps concerning the effectiveness of long-term field performance, the maximum reduction of the dose, and the economics of the Indian cotton production systems (Aljabali et al., 2025). Recent researchers have shown that the nano-pesticide formulations possess greater insecticidal effectiveness, less active ingredient dosage, and decreased environmental contamination due to a regulated release and increased selectivity (Liang et al., 2020). Field tests also suggest a lower non-target toxicity with enhanced sustainability as compared to the traditional formulations.

The current study was designed to come up with a stable nano-emulsional formulation of lambda-cyhalothrin and compare its relative field performance with H. armigera infesting cotton. The objectives were specific and were: (i) optimizing the parameters of nano-emulsions formulation and defining the physicochemical characteristics; (ii) measuring dose-dependent performance against target populations of pests; (iii) measuring the effect on yield parameters and crop economics; (iv) determining environmental benefits compared to conventional formulations. Despite these advantages, large-scale adoption of nano-pesticides faces regulatory challenges related to nano-specific risk assessment, environmental fate, and long-term ecological safety. The current study is relevant to solving the immediate problem of insufficient evidence-based sustainable pest management practices to balance the goals of productivity and ecological stewardship.

Key Contributions of the Present Study

The present study provides a comprehensive formulation-to-field evaluation of nano-emulsified lambda-cyhalothrin for sustainable management of *Helicoverpa Armigera* in cotton. In comparison to previous reports that rely on a lab characterization of the product, this article incorporates physicochemical optimization, 2-year field testing, cost analysis, and environmental performance measures. This paper has provided quantitative evidence of the fact that nano-emulsification remarkably improves the insecticidal properties with up to 89.3% of larval suppression at 20 g a.i./ha, reducing boll damage to 8.4%, and increasing seed cotton yield by 22.7% over conventional EC formulations while enabling a 25–30% reduction in active ingredient dosage. Also, there are enhanced rainfastness, UV stability, lowered off-target losses, and low non-target toxicity, which demonstrates the ecological benefit of nano-enabled formulations. All these results prove that nano-emulsified insecticides are a potential solution in enhancing effectiveness in the use of pests and also complement sustainability aims in cotton agroecosystems.

Organization of the Paper

The paper is structured in the following way. The Materials and Methods section include the formulation procedure, physicochemical description of the nano-emulsion, experimental plan, field analysis plans, and statistical calculations. In the Results and Discussion section, formulation properties, field bio efficacy, yield responses, economic returns, and environmental performance are given as compared to conventional formulations. The Conclusion is a summary of the most important numerical results, limitations of the present research, and future research directions of nano-pesticide application in sustainable pest management.

Materials and Methods

Particulars of the Experimental Site and the Crop

Two field experiments were carried out at the Research Farm of Chaudhary Charan Singh Haryana Agricultural University, Hisar (29.09º N, 75.71º E) in the semi-arid north Indian area during the kharif seasons of 2022 and 2023. The soil was sandy loam and had a pH of 7.8, organic carbon of 0.42, and available NPK of 185, 18.5, and 245 kg/ha, respectively. Sowing of cotton cultivar H-1117 (Brahma) was done on 15 May in both years, and the spacing of the rows and plants was 67.5 cm and 60 cm, respectively. The uniformity of the practice followed was to use no insecticidal application.

Test Insect

Bioassay studies were done on untreated cotton fields by collecting the *Helicoverpa Armigera* larvae and rearing them at 27 ± 2 C, 65 ± 5% Relative Humidity, and 14:10 L:D photoperiod at 27ºC in artificial diet (Armes et al., 1992). Field population tests were done on second to fourth instar larvae.

Nano-Emulsion Formulation

Lambda-cyhalothrin (95% purity, technical grade) was purchased from Tagros Chemicals

India Ltd. The process of making the oil-in-water nano-emulsion was through phase inversion temperature. The composition of the oil phase consisted of lambda-cyhalothrin (20g/L), Tween 80 (polyoxyethylene sorbitan monooleate, 4% v/v), and Span 20 (sorbitan monolaurate, 2% v/v) dissolved in medium-chain triglycerides. In the aqueous phase, the distilled water was used, having 0.5% polyvinyl alcohol as a stabilizer. Ultrasonication of the mixture was done at a 20kHz frequency, 70% amplitude at pulse mode (30s on, 10s off) with a probe sonicator (VCX 750, Sonics and Materials, USA) to avoid overheating. Dynamic light scattering was used to formulate the particle size, polydispersity index (PDI), and zeta potential (Zetasizer Nano ZS90, Malvern Instruments, UK). The stability was evaluated by centrifugation (10,000 rpm, 30 min) and storing at 4ºC, 25ºC, and 54ºC after 14 days as recommended by the CIPAC (EFSA, 2015). Tween-80 and Span-20 were selected based on their high hydrophilic-lipophilic balance compatibility and ability to produce stable nano-emulsions with lambda-cyhalothrin, while the active ingredient concentration was optimized to maximize efficacy and formulation stability.

Treatments and Experimental Design

There were five treatments in the experiment (T_1): Nano-emulsion at 10g a.i./ha, (T_2) Nano-emulsion at 15g a.i./ha, (T_3) Nano-emulsion at 20g a.i./ha, (T_4) Commercial EC formulation (Lambda-C 5% EC) at 20g a.i./ha (recommended dose), and (T_5) Untreated control. The experiment was set in a randomized complete block design (RCBD) that had three replications. The size of the gross plot was 6m by 5m (30m^2), consisting of four rows. The spray applications were done with the help of a knapsack sprayer (CP-3 nozzle), and a 500 L/ha spray volume was used at the time when H. armigera activity was at its peak (week three of August). Mean temperature (31.2ºC), RH (68), and wind speed (3.4 km/h) were recorded by the meteorological data at the moment of application. Field applications were conducted under uniform meteorological conditions, with temperature, relative humidity, and wind speed recorded at each spray event to minimize environmental variability.

Data Collection

The population of pests was observed at random by picking 10 plants in each plot and counting larvae on the vegetative and fruiting areas. It was observed on pre-treatment and 1, 3, 7, 10, and 15 days after treatment (DAT). The method used in the measurement of boll damage was tagging 50 bolls per plot and recording the damaged bolls with typical feeding holes. Parameters of yields were the total bolls per plant, boll weight, and the seed cotton yield (kg/ha) produced on the net plot area (4m × 3m). The 0-5 visual scale was used to record the symptoms of phytotoxicity at 3, 7, and 10 DAT.

Statistical Analysis

Data were pooled over two years as the interaction between year and treatment was non-significant. Analysis of variance (ANOVA) was performed using OPSTAT software (Gupta et al., 2022). Treatment means were compared using the least significant difference (LSD) test at $P \leq 0.05$. Percent reduction in larval population was calculated using the Henderson-Tilton formula:

$$\text{Percent reduction} = \left(1 - \frac{T_a \times C_b}{T_b \times C_a}\right) \times 100 \quad (1)$$

In equation (1), where T_a and T_b are post- and pre-treatment populations in treated plots, and C_a and C_b are post- and pre-treatment populations in control plots.

Results and Discussion

Optimized nano-emulsion had the mean droplet diameter of 126 ± 12 nm and PDI of 0.198, which has a narrow size distribution (Table 1). A -34.2mV Zeta potential gave the product excellent electrostatic stability. When the formulation was centrifuged, it did not separate into phases or cream. Storage stability tests indicated the degradation of active ingredients of less than 5% with 14 days at 54°C, which is within FAO specifications of commercial formulations. The viscosity was 4.8cP, which is easily mixed and sprayable. The presence of spherical droplets of homogenous morphology was confirmed with the help of transmission electron microscopy.

Table 1: Physicochemical Characteristics of Lambda-Cyhalothrin Nano-Emulsion Formulation

Parameter	Value	Standard Deviation
Mean particle size (nm)	126	±12
Polydispersity index	0.198	±0.018
Zeta potential (mV)	-34.2	±2.1
Viscosity (cP)	4.8	±0.3
pH	6.8	±0.2
Active ingredient content (g/L)	20.3	±0.4
Stability at 54°C (%)	95.8	±1.2

Given all the treatments of nano-emulsions, the population of larvae was significantly lower than the control (Table 2). T_3 at 3 DAT showed 76.4% reduction, which is much better than T_4 (62.3%). Optimal efficacy was realized at 7 DAT with T_3 reaching 89.3% reduction as opposed to 76.8 % when using conventional EC formulation. The increased efficacy at a lower dose (T_2 at 15g a.i./ha) corresponded to EC formulation efficacy, revealing the ability to reduce doses by 30% doses. In studies of persistence, nano-emulsion had a persistence of greater than 70% at 10 DAT, but declined to 58.4% at 7 DAT in EC formulations. This slow release is explained by a regulated release of nano-carriers and cuticular penetration with the help of stomatal uptake (Fincheira et al., 2023).

Table 2: Efficacy of Different Formulations Against *Helicoverpa Armigera* Larvae Population in Cotton (Pooled Data of 2022 and 2023)

Treatment	Dose (G A.I./Ha)	Mean Larval Population/Plant	Percent Reduction Over Control
		Pre-treatment	3 DAT
T_1: Nano-emulsion	10	4.2	67.44%
T_2: Nano-emulsion	15	4.3	74.42%
T_3: Nano-emulsion	20	4.1	79.07%
T_4: EC formulation	20	4.2	62.32%
T_5: Control	-	4.1	0%
LSD ($P \leq 0.05$)		0.38	0.31

The efficacy improvement was observed in accordance with studies on nano-encapsulated insecticides to cotton pests, in which better adhesion, UV protection, and controlled release led to better field performance than conventional preparations (Shawer et al., 2022; Liang et al., 2020). Decreased residue in the soil, decreased off-target loss, and low non-target toxicity in this study show that nano-emulsified insecticides are ecologically compatible in pest management (Ghulam & Farman, 2025).

In the test of the boll damage, high variations of treatments were made out (Table 3). T_3 had the lowest mean boll damage, 8.4 in both seasons, which was lower than 15.2 and 34.6 with T_4 and control, respectively. The results of dose-dependent response were observed in nano-emulsion treatments with T_1, T_2, and T_3, presenting with damage of 18.3, 12.7, and 8.4%, respectively. The yield qualities were also enhanced accordingly. T_3 had the maximum number of bolls per plant (42.6), maximum boll weight (4.8g), and, according to the yield, seed cotton was obtained (2,847 kg/ha). This was equivalent to 22.7% higher than the EC formulation (2,319 kg/ha) and 67.2 higher than the control. This yield benefit is due to good protection of crops at the most vital flowering and boll development phases when the H. armigera will inflict the most damage (Sharma and Parihar, 2020).

Table 3: Effect of Treatments on Boll Damage and Seed Cotton Yield in Cotton (Pooled Data)

Treatment	Boll Damage (%)	Bolls/Plant	Boll Weight (g)	Seed Cotton Yield (Kg/Ha)	Yield Increase Over Control (%)
T_1	18.3	36.4	4.2	2,245	31.8
T_2	12.7	39.8	4.5	2,564	50.5
T_3	8.4	42.6	4.8	2,847	67.2
T_4	15.2	37.2	4.3	2,319	36.2
T_5	34.6	28.4	3.6	1,703	-
LSD ($P \leq 0.05$)	2.14	3.8	0.32	186	

The cost-benefit analysis indicated that T_3 offered the best net returns of 1,24,680/ha with a benefit-cost ratio of 1:2.84 (Table 4). Formulation cost was 15% more than EC, but superior efficacy allowed 25% less dose in T_3 with better control, which compensates for the start-up cost. There were some extra yields of 18,420/ha over conventional treatment, which were largely attributable to the yield premium and decreased frequency of application. Partial budgeting revealed that nano-emulsion at 15 g a.i./ ha (T_2) had ideal economic efficiency to marginal farmers, which would yield 90% of T_3 efficacy with half the cost of input.

Table 4: Economics of Different Lambda-Cyhalothrin Formulations in Cotton Cultivation

Treatment	Cost Of Insecticide (₹/Ha)	Application Cost (₹/Ha)	Total Cost (₹/Ha)	Gross Returns (₹/Ha)	Net Returns (₹/Ha)	B: C Ratio
T_1	1,850	750	2,600	89,800	87,200	1:2.51
T_2	2,775	750	3,525	1,02,560	99,035	1:2.81
T_3	3,700	750	4,450	1,13,880	1,09,430	1:2.59
T_4	3,200	1,125	4,325	92,760	88,435	1:2.45
T_5	0	0	0	68,120	68,120	-

*Prices based on 2023 rates: Seed cotton ₹40/kg

Nano-emulsion showed high rainfastness, 85% retention following simulated rainfall (25mm/h over 30min) as compared to 52 % of EC formulation. The analysis of the UV stability revealed that 92% active ingredient retention was observed after 8h exposure compared to 68% in the conventional formulation. The off-target losses were minimized by reduced droplet bounce-off and a high spreading coefficient (contact angle 28° vs 52° EC). According to environmental fate modelling, the soil accumulated residue was reduced by 40%, and the potential of leaching was also decreased with nano-encapsulation. These features are consistent with the principles of sustainable intensification since they prevent the further use of chemical loads and ensure pest control (Karimi-Maleh et al., 2024).

Phytotoxicity symptoms were not found at any time during any of the nano-emulsion treatments. Subsequent wheat crop germination tests did not respond to allelopathic effects. The non-target organism biosafety tests showed that, in 7 DAT field-weathered residues, *Coccinella septempunctata* (3.2) and *Chrysoperla carnea* (1.8) were exposed to residues with negligible mortality compared to the EC formulation (12.4 and 8.6, respectively). This is a favor of selectivity, which promotes the adoption of integrated pest management.

The current results are supported by the recent studies of nano-pesticides that show an increased effectiveness due to the increase in delivery kinetics (Shawer et al., 2022). The adverse zeta potential inhibited the coalescence of the droplets and promoted the electrostatic adhesion to negative leaf surfaces. Controlled release properties prolonged residual life, lowered usage frequency, and reduced workforce expenses.

Nevertheless, extended outcomes on the microbiota of soil and the development of resistance mechanisms should be monitored (Kapeleka & Mwema, 2024). Regulatory frameworks should also be changed to deal with the nano-specific risk assessment and foster innovation in sustainable agriculture.

Conclusion

This paper has proven beyond any doubt that nano-emulsification of lambda-cyhalothrin has a significant positive effect on its field activity against *Helicoverpa Armigera* and allows for the reduction of the dosage of pesticide. The nano-emulsion with the optimized size of 126 ± 12 nm mean droplet size, a small size distribution (PDI 0.198), and a high electrostatic stability (−34.2mV) demonstrated a better physicochemical stability and successful release. Nano-emulsified lambda-cyhalothrin 20g a.i. ha^{-1} under field conditions showed 89.3% larval suppression, 7 days post-treatment, which was far better than the conventional EC formulation (76.8%). The level of boll damage was lower at 8.4 % than it was under EC conditions of 15.2 %, and this led to 22.7 % seed cotton (2,847 kg ha^{-1}).

Increased foliar adhesion, rainfastness (85% retention), and UV stability (92% active ingredient retention) all helped increase foliar residual activity and minimize off-target loss. Economic analysis also confirmed a better net return and benefits-to-costs ratio, although formulation cost was marginally increased. Notably, the nano-emulsion was not phytotoxic or had a high lethality against non-target useful arthropods, arguing in its favor with the integrated pest management.

The experiment was held at one agro-ecological site and two cultivating seasons, and the effects of prolonged studies on soil microbiota and resistance evolution, as well as ecosystem services, were not investigated. The present work was also not within the scope of regulatory considerations and large production feasibility on a large scale.

The direction of further research is multi-location and multi-year field validation, testing of resistance development during long-term exposure to nano-pesticides, interaction with the microbial communities of soils, and extensive nano-specific environmental risk evaluation. To ease regulatory compliance and increase the broader use of nano-enabled insecticides to manage cotton pests sustainably, it will be necessary to address these aspects.

Conflict of Interest

The authors declare that they do not have any conflict of interest.

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