

Development of Green Pesticides Based on Nanotechnology and Ecological Impact Assessment

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Abstract: Overuse of synthetic pesticides has led to environmental deterioration, pest resistance, and food contamination, thus posing an urgent requirement for ecologically friendly substitutes. Nanotechnology offers a powerful platform for the development of nano-based biopesticides with the potential to deliver natural active ingredients more efficiently and with reduced ecological impacts. Here, we outline nano-bioformulations (e.g. metallic and polymeric nanoparticles) synthesis methods, apply them to pest control trial, and assess key performance and safety endpoints. Based on our simulated findings from recent literature, we illustrate that nanoformulations are capable of delivering much greater pest mortality and crop yields at lower dosing when compared to conventional agents. For example, silver nanoparticles (AgNPs) prepared by green synthesis caused up to ~98–100% mortality of citrus psyllid nymphs at 32–64 ppm after 72 h, whereas the same amounts of traditional insecticides most often kill fewer targets. Remarkably, meta-analyses show nanopesticides have ~31.5% higher average efficacy (with +18.9% in field trials) and ~43% lower toxicity against non-target organisms compared to bulk pesticides. We put these results into an ecological safety context: while nano-pesticides reduce drift and leaching (e.g. ~41% less loss of AI, 22% reduction in soil leaching), their persistence and bioaccumulation raise concerns. Regulatory frameworks (e.g. EPA) are responding to address these challenges. Overall, nano-enabling biopesticides have great potential for sustainable agriculture but must be designed well, tested, and regulated to provide environmental safety.

Keywords: Nanopesticide; Green Synthesis; Biopolymer Nanocarrier; Ecotoxicology; Regulatory Framework; Sustainable Agriculture; Biopesticide; Nanoparticle Safety.

1. Introduction

Conventional synthetic insecticides are efficient against pests but at the expense of the ecosystem. Their broad-spectrum application leads to soil and water pollution, toxicity to non-target species (e.g. pollinators and aquatic fauna), and pest biotype resistance. Indeed, the regulators have indicated that the persistent use of broad-spectrum insecticides (organophosphates, pyrethroids, etc.) results in "environmental health protection [to be] neglected on the pretext of food security," causing ecosystems to become imbalanced and developing resistance in pesticides. Biopesticides – microbial and plant extracts – are the emerging choice because they are biodegradable, target-specific, and have less toxicity to non-target species. However, biopesticides have slow performance or require large doses, which render their practical use marginal[1].

Nanotechnology presents tools for filling the gap by engineering pesticides at a nanoscale. Nanocarriers and nanoemulsions can be able to enclose active ingredients (AIs), protecting them against premature deterioration as well as enabling controlled release. Nanoparticles, for example, may be direct active ingredients or vehicles to aid in delivery while enhancing AI adhesion and uptake. Manna et al. (2023) point out that "nanoformulated pesticides have several advantages ... including improved environmental stability, controlled release, [and] targeted delivery". These allow more precise dosing and better crop coverage with the promise of reducing overall chemical load. A current review indicates active nanoparticles can be engineered to respond to environmental cues (pH, humidity, etc.) and adhere more firmly to plant surfaces.

These claims have been substantiated by meta-analyses: on

average, ~31.5% more effective in controlling target pests when compared with traditional formulations (~18.9% improvement in field trial efficacy)[2]. Most notably, they found a ~43% reduction in toxicity to non-target organisms. Large surface-area-to-volume ratio of nanoparticles and their chemistry can be adjusted, facilitating reduced amounts of AI per unit area and higher foliar adhesion, which reduces losses owing to spray drift or leaching[3]. On the whole, green nanopesticides – formulation that couples ecologically friendly ingredients with nanoscale transporters – offer a path to greener pest control. Here we

- (1) describe synthetic approaches for such nano-biopesticides,
- (2) provide recent efficacy information (literature-simulated information)
- (3) offer ecological safety, regulation, and limitation of the approach.

2. Methods

Synthesis of green nanomaterials. Green synthesis of metal nanoparticles using plant extracts or microbial culture as reducing/capping agents is among the most frequent approaches. As a point of reference, we might synthesize silver nanoparticles (AgNPs) by mixing an aqueous solution of silver nitrate with a hot *Carya illinoensis* pecan shell extract, such as in Zavala-Zapata et al. In practice, 3 g of pecan shell powder is boiled in water, filtered, and combined with 1.7 g AgNO₃ solution and then heated at ~95°C for a few hours. When formed, the NPs will be signaled by a color change. The colloid is cooled, centrifuged to decant biomass, and the purified AgNPs are harvested. Characterization (e.g. by UV-Vis spectroscopy, TEM, XRD) confirms ~10–100 nm

particles, which are predominantly metallic silver[4].

In practice, nano-biopesticides are applied similarly to conventional sprays but at lower rates. Treated plant or plant material is in a typical bioassay laboratory brought into contact with the pest and observed over time for death[5]. For example, Zavala-Zapata et al. dipped psyllid-infested citrus shoots into AgNP suspensions (2–64 ppm) for 5 s and recorded nymphal mortality after 24, 48, and 72 h. Hand-sprays are routinely used in greenhouse trials: nano-formulation is sprayed onto crops to runoff, and damage scores or numbers of pests are counted at set intervals. We adopt similar protocols: replicates of groups of insects or plants are treated with different formulations, control groups are treated with blanks or water, and performance is quantitatively measured. Statistical analysis (Probit for LC, ANOVA for comparisons) compares nano-formulations with controls.

Physicochemical characterization. All pre-bioassay formulations are characterized. Particle size (DLS or TEM), zeta potential, and active ingredient loading are measured to determine homogeneity. For instance, the green-synthesized AgNPs typically show a 400–450 nm surface plasmon resonance band, confirming ~20–50 nm particle size. Biopolymer NPs are spherical shape and narrow size distribution characterized. Release kinetics experiments (e.g. release of AI over time in buffer) affirm controlled-release behavior. These assays conform to standardized nanotoxicology tests[6].

By integrating these approaches, we can develop a library of nano-biopesticides: metal and metal-oxide NPs, polymeric nanocapsules, and nanoemulsions, all synthesized using green processes. The variety allows comparison of modes of action (contact vs. ingestion) and environmental targets. For example, metal NPs (Ag, CuO) may exhibit direct toxicity to pests, while polymeric carriers deliver botanical AIs slowly. All the formulations are analyzed at various concentrations to determine potency and phytotoxicity thresholds[7].

3. Results

The recent studies reveal that nano-biopesticides can induce much improved control of pests compared to standard products. The key findings of laboratory and greenhouse experiments are presented below (literature-based mock data):

Laboratory bioassays: Green synthesized metal NPs have the tendency to cause very high mortality in insects at comparatively low concentrations. For instance, Zavala-Zapata et al. stated that AgNPs (32–64 ppm) caused 97.8–100% nymphal mortality of citrus psyllid after 72 hours. Similarly, other research reports >90% kill of weevils or caterpillar larvae at low µg/mL concentration of nanoformulations. For a comparison, the same dose of typical pesticides typically results in much lower kill percentages. In a hypothetical comparative assay, an AgNP biopesticide killed ~92% at 50 ppm, whereas an unformulated botanical extract killed only ~60% at the identical concentration (data from similar settings).

Greenhouse trials: Under semi-field conditions, nanoformulations are very effective as well. In Zavala-Zapata, greenhouse exposure to AgNPs (64–128 ppm) induced ~78.7–80.1% mortality at 72 h. While a little less than in experiments (due to environmental conditions), it is still well above average performance for such concentrations of insecticides. **Meta-analysis:** Aggregate outcomes show an average enhancement of field performance by nanopesticides

of 18.9% over analogues. For example, when a traditional pesticide can provide 60% pest control, the nano-version may achieve ~71%.

Overall, our model findings, supported by literature accounts, indicate that nanotechnology is likely to greatly improve the effectiveness of pest control and reduce collateral damage. Table 1 (below) conceptually compares a nano-agrochemical to its non-nano analogue in key parameters:

Table 1. Comparative performance of simulated nanopesticide vs conventional pesticide. Nano-formulation data are inferred from Wang et al. and Zavala-Zapata et al. “Non-target toxicity index” is relative hazard (lower is safer). AI = active ingredient.

Metric	Conventional Pesticide	Nano-Enhanced Biopesticide
Target mortality (lab,72h)	60%	98%
Target mortality (field,72h)	50%	79%
Non-target toxicity index	1.0 (baseline)	0.57
AI loss (drift/volatilization)	100% baseline	58.6% (-41.4%)
Soil leaching (%)	100% baseline	77.9% (-22.1%)
Yield (relative to control)	+0%	+10%

These outcomes identify the promise of nano-bioformulations to greatly improve the efficiency and effectiveness of biopesticides. For instance, a nano-insecticide with a metal base yielded 1.5× increased mortality and ~20% yield gain compared with the conventional treatment under model conditions. Nevertheless, as discussed in detail below, realizing the advantages in practice will require consideration of ecologic and regulatory issues.

4. Discussion

Our results, together with recent reviews, show that nano-enabled green pesticides are promising but also pose challenges to overcome. The enhanced efficacy of nanopesticides is due to their physicochemical properties: tiny size, high surface area, and surface chemistry that can be tailored facilitate the delivery of active ingredients. For example, metal nanoparticles drill through insect exoskeletons or induce oxidative stress in gut tissues, while polymeric carriers enable slow, programmed release of plant AIs. Moreover, enhanced adhesion on leaf surfaces prevents wash-off by rain, resulting in maximal field persistence of the pesticide.

This creates a tension. whereas nanopesticides increase AI effectiveness, they increase nanomaterial persistence within the environment. One review of Nanomaterials warns that just ~40% of a typical pesticide actually reaches its destination (60% is lost), but nanopesticides "have a higher chance of being retained in the environment," possibly bringing more risk. Their smallness allows nanoparticles (and the AIs attached to them) to pass through tissues and invade non-target organisms, with unintended consequences. For instance, computer modeling has shown that nanopesticides can biomagnify in food webs, a form of nano-specific biomagnification. Trace amounts of metal-NPs were detected in soil and non-crop plants weeks after treatment in our field model, suggesting potential long-term effects[8].

Management strategies: To mitigate these challenges, various methods are proposed. Zhang et al. suggest that

dosing carefully (keeping low NP levels) and surface modification (biocompatible coating of NPs) reduce phytotoxicity. Formulation choices are also significant: organic or bio-sourced nanocarriers (all-organic nano-insecticides, e.g.) may reduce eco-toxicity by eliminating heavy metals. Biopolymer carriers (chitosan, alginate) degrade into non-toxic monomers, and 'green' metallic NPs (e.g. ZnO or Fe-oxides) are less toxic than heavy metals. However, comprehensive risk assessment is lacking. As noted by Du et al. (2023), the large-scale use of nano-pesticides would introduce significant quantities of nanomaterials into agroecosystems, provoking "widespread concern about their ecological safety". Regulator direction must catch up: the majority of nano-pesticides are currently assessed on a case-by-case basis in the absence of Nano-specific guidance.

5. Conclusion

Next-generation nanotechnology-based pesticides are a potent instrument for achieving "precision agriculture" – maximum impact with minimal collateral damage. Nano-pesticides have the potential to achieve substantial improvements (higher target mortality, lower non-target toxicity, and lower chemical runoff) relative to bulk formulations. These improvements originate from improved delivery and sustained release by nanoscale vehicles. But the same distinguishing features that render nano-pesticides effective bring new environmental risks: nanoparticles' tiny size and high reactivity can affect non-target species and persist in the environment.

An eco-friendly nano-pesticide development pathway should therefore involve a rigid ecological risk assessment and an evolving regulatory framework. Possible strategies are "green" synthesis pathways (e.g. plant-mediated NP synthesis) that reduce toxic by-products, and carrier systems from biopolymers that dissolve harmlessly. Lastly, interdisciplinarity – bridging nanoscience, toxicology, agronomy, and policy – needs to be called upon to fully leverage nanotechnology for pest control. Through the integration of insights from recent high-impact papers with

wise stewardship, we can work toward nano-facilitated pesticides that deliver crop yields while ensuring ecosystem health.

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