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Nanopesticides in Modern Agriculture: Recent Advances, Mechanisms of Action, Environmental Safety, and Future Prospects

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Abstract

Nanopesticides have emerged as an innovative approach for improving crop protection while reducing the environmental impacts associated with conventional pesticides. By utilizing nanotechnology, nanopesticides offer controlled release, targeted delivery, enhanced stability, and improved bioavailability of active ingredients, resulting in increased pest control efficiency with lower chemical usage. These nano-enabled formulations help minimize pesticide residues, reduce environmental contamination, and support sustainable agricultural production. Recent advances in nanomaterials, precision agriculture, and smart delivery systems have expanded the applications of nanopesticides in managing insects, weeds, fungi, and plant diseases. However, concerns regarding nanoparticle toxicity, environmental persistence, regulatory policies, and food safety remain important challenges. This review provides a concise overview of nanopesticides, their mechanisms of action, recent technological developments, environmental safety aspects, current challenges, and future prospects for sustainable crop protection.

Keywords: *Nanopesticides, Nanotechnology, Sustainable Agriculture, Crop Protection, Environmental Safety, Precision Agriculture, Pest Management.*

1. Introduction

Agricultural productivity is continuously threatened by insects, weeds, fungi, bacteria, and other plant pathogens that cause significant crop losses worldwide [1,2]. Conventional chemical pesticides have played an essential role in crop protection; however, their excessive and repeated use has resulted in environmental pollution, pesticide resistance, soil degradation, and risks to human and animal health [3,4]. These limitations have created an urgent need for safer and more efficient crop protection technologies that support sustainable agricultural development. Nanotechnology has emerged as a promising solution by introducing nanopesticides, which improve the delivery and performance of pesticide formulations [5,6]. Nanopesticides consist of nano-sized particles or nano-carriers that enhance the stability, solubility, and controlled release of active ingredients. Compared with conventional pesticides, nanopesticides require lower application rates, provide prolonged protection, and reduce off-target effects, thereby minimizing environmental contamination [2,7,8]. Recent developments in nanomaterials, biotechnology, and precision agriculture have accelerated the adoption of nanopesticides in modern farming [9,10]. Various nanomaterials, including metal nanoparticles, polymeric nanoparticles, silica nanoparticles, and nanoemulsions, are being developed to improve pest management efficiency. These technologies not only increase crop productivity but also reduce production costs and chemical residues in agricultural ecosystems [11,12]. Despite their significant advantages, concerns regarding nanoparticle toxicity, environmental persistence, ecological impacts, and regulatory approval remain major challenges [13,14]. Comprehensive risk assessment and standardized safety guidelines are necessary to ensure the responsible use of nanopesticides [15,16]. This review summarizes recent advances in nanopesticides, their mechanisms of action, environmental safety, major applications, current limitations, and future research directions for sustainable crop protection.

2. Overview of Nanopesticides

Nanopesticides are pesticide formulations that utilize nanotechnology to improve the delivery, effectiveness, and stability of active ingredients [2,5]. These formulations may contain nanoparticles as active agents or as carriers that transport pesticides directly to target pests. Common nanopesticide systems include polymeric nanoparticles, metal nanoparticles, nanoemulsions, liposomes, and silica-based nanocarriers [6,9]. Their small particle size allows better penetration into plant tissues and improved interaction with target organisms, resulting in enhanced pest control and reduced chemical losses [10,11].

3. Mechanisms of Action of Nanopesticides

Nanopesticides improve pest control through several mechanisms [7,8]. Controlled-release formulations gradually release active ingredients over time, extending their effectiveness and reducing repeated pesticide applications [2,5]. Targeted delivery systems ensure that pesticides reach specific pests or infected plant tissues while minimizing effects on non-target organisms [10,12]. Some metal nanoparticles possess direct antimicrobial or insecticidal activity by disrupting cellular membranes, generating reactive oxygen species, or interfering with essential metabolic processes [17,18]. These mechanisms improve pesticide efficiency while reducing environmental contamination.

4. Recent Advances in Nanopesticide Technology

Recent progress in nanotechnology has led to the development of advanced nanopesticide formulations with improved stability, biodegradability, and environmental compatibility [6,9]. Nanoencapsulation techniques protect active ingredients from degradation caused by sunlight, temperature, and moisture [5,10]. Smart nanopesticides capable of responding to environmental stimuli such as pH, temperature, or moisture are also being developed for precision agriculture [18,19]. In addition, artificial intelligence and sensor technologies are increasingly integrated with nanopesticide applications to optimize dosage and application timing [20].

5. Applications in Modern Agriculture

Nanopesticides are widely applied for controlling insects, fungal diseases, bacterial infections, nematodes, and weeds in agricultural crops [3,6]. They are used in cereals, fruits, vegetables, oilseed crops, and horticultural production systems. Their high efficiency allows farmers to reduce pesticide consumption while maintaining effective crop protection [2,11]. Nanopesticides also contribute to integrated pest management (IPM) strategies by supporting sustainable farming practices and minimizing environmental impacts [9,17].

6. Environmental Safety and Risk Assessment

Environmental safety remains one of the most important considerations for nanopesticide applications [13,14]. Controlled-release formulations reduce chemical runoff and groundwater contamination compared with conventional pesticides [5,8]. However, long-term accumulation of nanoparticles in soil and aquatic environments may affect beneficial microorganisms, insects, aquatic organisms, and biodiversity [15,16]. Comprehensive toxicity studies, environmental monitoring, and life-cycle assessments are necessary to evaluate the ecological impacts of nanopesticides before large-scale commercialization [1,20].

7. Challenges and Future Prospects

Although nanopesticides offer numerous advantages, several challenges limit their widespread adoption [13,15]. High production costs, limited commercial availability, insufficient long-term safety data, and inconsistent regulatory frameworks remain major barriers [14,16]. Future research should focus on developing biodegradable nanomaterials, environmentally friendly formulations, and internationally accepted regulatory standards [18,19]. Advances in precision agriculture, smart sensors, artificial intelligence, and nanobiotechnology are expected to further improve the efficiency and safety of nanopesticide technologies [10,20].

Table 1: Types of Nanopesticides, Mechanisms of Action, and Agricultural Benefits

Type of Nanopesticide	Mechanism of Action	Major Agricultural Benefits
Metal Nanoparticles (Ag, Cu, ZnO)	Disrupt microbial cell membranes and generate reactive oxygen species (ROS)	Effective control of plant pathogens and improved crop protection
Polymeric Nanoparticles	Controlled and targeted release of pesticide active ingredients	Reduced pesticide application and prolonged effectiveness
Nanoemulsions	Enhance solubility, stability, and penetration of pesticides	Improved pest control efficiency with lower chemical dosage
Silica-Based Nanocarriers	Encapsulate pesticides for slow and sustained release	Reduced environmental contamination and improved pesticide utilization
Lipid-Based Nanocarriers (Liposomes)	Improve delivery and bioavailability of pesticides	Enhanced efficacy and reduced off-target effects

8. Conclusion

Nanopesticides represent an important advancement in modern agriculture by providing efficient, targeted, and environmentally friendly crop protection solutions. Their controlled-release properties, enhanced stability, and improved pest control efficiency contribute to sustainable agricultural production while reducing chemical inputs and environmental pollution. Although concerns regarding environmental safety and regulatory approval remain, continuous research and technological innovations are expected to support the safe integration of nanopesticides into future agricultural systems. These developments will play a significant role in improving global food security and promoting sustainable crop protection.

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