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Nanopesticides for Sustainable Crop Protection: Formulation Strategies, Biological Efficacy, and Regulatory Challenges

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ABSTRACT

Nanopesticides have emerged as an innovative approach for sustainable crop protection by improving pesticide delivery, increasing biological efficacy, and minimizing environmental pollution. Compared with conventional pesticides, nanopesticides provide controlled release, enhanced stability, improved target specificity, and reduced chemical losses. Various formulation strategies, including nanoemulsions, polymeric nanoparticles, liposomes, and inorganic nanocarriers, have significantly enhanced the performance of pesticide active ingredients while reducing application frequency. Nanopesticides also support integrated pest management and precision agriculture by improving pest control efficiency and reducing adverse effects on non-target organisms. Despite these advantages, concerns regarding nanoparticle toxicity, environmental persistence, food safety, and regulatory approval remain major challenges for commercialization. This review summarizes recent developments in nanopesticide formulation strategies, biological efficacy, agricultural applications, regulatory issues, and prospects for sustainable crop protection.

Keywords: *Nanopesticides, Sustainable Agriculture, Crop Protection, Nanoformulations, Biological Efficacy, Precision Agriculture, Nanotechnology.*

1. Introduction

Agricultural production faces continuous threats from insects, fungi, bacteria, nematodes, and weeds that significantly reduce crop productivity worldwide [1,2]. Chemical pesticides have been widely used to control these pests; however, excessive and indiscriminate pesticide application has resulted in environmental pollution, pesticide resistance, biodiversity loss, and health risks to humans and animals [3,4]. These concerns have increased the demand for safer and more sustainable crop protection technologies. Nanotechnology has introduced nanopesticides as an advanced alternative to conventional pesticide formulations [5,6]. Nanopesticides utilize nanomaterials as carriers or active ingredients to improve pesticide stability, controlled release, solubility, and targeted delivery. Their nanoscale size enhances interaction with plant surfaces and pest organisms, resulting in greater biological efficacy while reducing pesticide losses and environmental contamination [7,8].

Recent developments in nanotechnology, biotechnology, and precision agriculture have accelerated the development of novel nanopesticide formulations [9,10]. Nanoencapsulation, polymeric nanocarriers, silica nanoparticles, metal nanoparticles, and nanoemulsions are increasingly being investigated for efficient pest management. These technologies improve crop protection while reducing chemical inputs, supporting sustainable agricultural production [11,12].

Despite their promising applications, several challenges remain regarding environmental safety, nanoparticle toxicity, food safety, and regulatory approval [13,14]. Standardized risk assessment methods and international regulatory frameworks are essential for the responsible commercialization of nanopesticides [15,16]. This review discusses formulation strategies, biological efficacy, agricultural applications, regulatory challenges, and future prospects of nanopesticides for sustainable crop protection [17–20].

2. Overview of Nanopesticides

Nanopesticides are pesticide formulations developed using nanotechnology to improve the delivery and performance of active ingredients [2,5]. They may contain nano-sized active ingredients or nanocarriers that transport conventional pesticides to target organisms. Common nanopesticide formulations include nanoemulsions, polymeric nanoparticles, liposomes, silica nanoparticles, metal nanoparticles, and nanocapsules [6,9]. Their small particle size improves penetration through plant tissues and insect cuticles while enhancing pesticide stability and reducing degradation caused by sunlight, moisture, and temperature [8,10]. These characteristics enable effective pest control with lower pesticide doses and fewer field applications [11,12].

3. Formulation Strategies of Nanopesticides

Advanced formulation strategies play an important role in improving the efficiency and safety of nanopesticides [5,7]. Nanoencapsulation protects pesticide active ingredients from environmental degradation while enabling slow and controlled release according to crop requirements [6,8]. Polymeric nanoparticles and biodegradable nanocarriers provide sustained pesticide delivery, reducing repeated applications and minimizing environmental contamination [10,13].

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Nanoemulsions improve the solubility and dispersion of poorly soluble pesticides, resulting in enhanced biological activity [9,11]. Lipid-based nanocarriers and silica nanoparticles further improve pesticide stability, target specificity, and compatibility with integrated pest management systems [12,15]. These formulation strategies significantly improve pesticide utilization efficiency while supporting environmentally sustainable crop protection [16,18].

4. Biological Efficacy in Crop Protection

Nanopesticides exhibit enhanced biological efficacy compared with conventional pesticides due to their improved delivery systems, controlled release, and increased interaction with target pests [4,6]. Their nanoscale size facilitates better adhesion to plant surfaces and efficient penetration into insect cuticles, fungal hyphae, and bacterial cell walls, resulting in higher pesticidal activity [7,9]. Controlled-release formulations maintain an effective concentration of active ingredients for extended periods, reducing the need for repeated applications [5,8]. Several studies have demonstrated that nanopesticides effectively control a broad range of agricultural pests, including insects, fungi, bacteria, nematodes, and weeds, while requiring lower application rates than conventional pesticides [10,12]. This increased biological efficacy contributes to improved crop protection, higher agricultural productivity, and reduced pesticide residues in food and the environment [13,15].

Table 1: Major Nanopesticide Formulation Strategies and Their Agricultural Benefits

Formulation Strategy	Description	Major Agricultural Benefits
Nanoemulsions	Nanoscale oil-in-water or water-in-oil emulsions containing pesticide active ingredients	Improved solubility, enhanced bioavailability, greater pesticide efficacy, and reduced application rates
Polymeric Nanoparticles	Biodegradable polymer-based carriers encapsulating pesticide molecules	Controlled and sustained release, prolonged pesticidal activity, and reduced environmental contamination
Liposomes	Lipid-based vesicles used to encapsulate and deliver pesticide active ingredients	Enhanced target-specific delivery, improved stability, and reduced degradation of active compounds
Silica Nanocarriers	Mesoporous silica nanoparticles used for pesticide loading and controlled release	Increased stability, controlled release, improved pesticide retention, and minimized chemical losses
Metal and Metal Oxide Nanoparticles	Silver (Ag), copper (Cu), zinc oxide (ZnO), and other metallic nanoparticles with intrinsic pesticidal properties	Direct antimicrobial, antifungal, and insecticidal activity, resulting in improved crop protection

Table 2: Advantages and Regulatory Challenges of Nanopesticides

Aspect	Advantages	Regulatory Challenges
Pesticide Efficiency	Enhanced pest control with lower pesticide doses and improved efficacy	Lack of standardized testing and evaluation protocols
Environmental Impact	Reduced pesticide runoff, environmental residues, and off-target contamination	Limited information on long-term environmental fate and ecological impacts
Crop Protection	Controlled release, improved stability, and prolonged protection against pests and pathogens	Insufficient toxicity data for non-target organisms and beneficial species
Precision Agriculture	Target-specific delivery and reduced frequency of pesticide applications	Need for internationally harmonized regulatory frameworks and risk assessment guidelines
Commercialization	Promotes sustainable crop protection and integrated pest management (IPM)	High production costs, limited commercial-scale production, and lengthy regulatory approval processes

5. Applications in Sustainable Agriculture

Nanopesticides have become valuable tools for sustainable agriculture by improving pest management while reducing environmental impacts [2,5]. They are widely used for controlling insect pests, fungal diseases, bacterial infections, and weeds in cereals, fruits, vegetables, oilseed crops, and horticultural plants [6,11]. Nano-enabled pesticide formulations improve the precision of pesticide application by delivering active ingredients directly to target organisms, thereby minimizing damage to beneficial insects and other non-target species [8,10]. Integration of nanopesticides with precision agriculture technologies, remote sensing, and smart spraying systems further enhances pesticide efficiency and reduces unnecessary chemical application [14,16]. These developments support integrated pest management (IPM) programs and contribute to environmentally sustainable farming systems [17,18].

6. Regulatory Challenges and Safety Concerns

Despite their considerable advantages, nanopesticides present several regulatory and environmental challenges that must be addressed before widespread commercialization [13,14]. The behavior of nanoparticles in soil, water, and plant systems differs from that of conventional pesticides, making environmental risk assessment more complex [15,16]. Potential accumulation of nanoparticles may affect beneficial microorganisms, pollinators, aquatic organisms, and soil biodiversity if not properly managed [7,19]. In addition, many countries currently lack harmonized regulatory guidelines for evaluating nanopesticides, including standardized methods for toxicity assessment, environmental monitoring, labeling, and commercialization [18,20]. Comprehensive safety evaluations and internationally accepted regulatory frameworks are therefore essential to ensure responsible use of nanopesticides in agriculture.

7. Future Perspectives

Future research should focus on developing environmentally friendly, biodegradable, and highly efficient nanopesticide formulations that minimize ecological risks while maximizing crop protection [6,11]. Advances in biodegradable polymeric nanocarriers, nanoencapsulation technologies, and smart responsive delivery systems are expected to further improve pesticide performance [8,14]. Integration of nanopesticides with artificial intelligence (AI), Internet of Things (IoT), biosensors, drones, and precision agriculture technologies will enable real-time pest monitoring and site-specific pesticide application [9,17]. Collaborative efforts among researchers, regulatory agencies, and agricultural industries will accelerate the safe commercialization of nanopesticides and promote sustainable crop protection worldwide [19,20].

8. Conclusion

Nanopesticides have emerged as innovative tools for sustainable crop protection by improving pesticide delivery, enhancing biological efficacy, and reducing environmental pollution. Advanced formulation strategies such as nanoencapsulation, polymeric nanoparticles, nanoemulsions, and silica-based nanocarriers have significantly improved pesticide stability, controlled release, and target specificity. These technologies contribute to efficient pest management while supporting integrated pest management and precision agriculture. Although concerns regarding nanoparticle toxicity, environmental persistence, and regulatory approval remain important challenges, ongoing research continues to develop safer and more sustainable nano-enabled pesticide systems. Future advances in nanotechnology, smart agriculture, and digital farming are expected to enhance global food security while minimizing the environmental impacts of crop protection practices.

References

1. Kah, M., Beulke, S., Tiede, K., & Hofmann, T. (2013). Nanopesticides: State of knowledge, environmental fate, and exposure modeling. *Critical Reviews in Environmental Science and Technology, 43*(16), 1823–1867. https://doi.org/10.1080/10643389.2012.671750
2. Gogos, A., Knauer, K., & Bucheli, T. D. (2012). Nanomaterials in plant protection and fertilization: Current state, foreseen applications, and research priorities. *Journal of Agricultural and Food Chemistry, 60*(39), 9781–9792. https://doi.org/10.1021/jf302154y
3. Khot, L. R., Sankaran, S., Maja, J. M., Ehsani, R., & Schuster, E. W. (2012). Applications of nanomaterials in agricultural production and crop protection: A review. *Crop Protection, 35*, 64–70. https://doi.org/10.1016/j.cropro.2012.01.007
4. Mishra, S., Singh, H. B., & Keswani, C. (2017). Nanotechnology in agriculture: Opportunities, challenges, and future perspectives. *Journal of Pharmacognosy and Phytochemistry, 6*(5), 1689–1693.
5. Pérez-de-Luque, A., & Rubiales, D. (2009). Nanotechnology for parasitic plant control. *Pest Management Science, 65*(5), 540–545. https://doi.org/10.1002/ps.1732
6. Chen, H., & Yada, R. (2011). Nanotechnologies in agriculture: New tools for sustainable development. *Trends in Food Science & Technology, 22*(11), 585–594. https://doi.org/10.1016/j.tifs.2011.09.004
7. P. C., & Fraceto, L. F. (2014). Application of nanotechnology for the encapsulation of botanical insecticides for sustainable agriculture. *Journal of Agricultural and Food Chemistry, 62*(31), 7411–7420. https://doi.org/10.1021/jf502326f
8. Kah, M., & Hofmann, T. (2014). Nanopesticide research: Current trends and future priorities. *Environment International, 63*, 224–235.
9. Kah, M., Beulke, S., Tiede, K., & Hofmann, T. (2013). Nanopesticides: State of knowledge, environmental fate, and exposure modeling. *Critical Reviews in Environmental Science and Technology, 43*(16), 1823–1867.
10. Chen, H., & Yada, R. (2011). Nanotechnologies in agriculture: New tools for sustainable development. *Trends in Food Science & Technology, 22*(11), 585–594.
11. DeRosa, M. C., Monreal, C., Schnitzer, M., Walsh, R., & Sultan, Y. (2010). Nanotechnology in fertilizers. *Nature Nanotechnology, 5*(2), 91.
12. Nair, R., Varghese, S. H., Nair, B. G., et al. (2010). Nanoparticulate material delivery to plants. *Plant Science, 179*(3), 154–163.
13. Tsuji, J. S., Maynard, A. D., Howard, P. C., et al. (2006). Research strategies for safety evaluation of nanomaterials. *Toxicological Sciences, 89*(1), 42–50.
14. Nel, A., Xia, T., Mädler, L., & Li, N. (2006). Toxic potential of materials at the nanolevel. *Science, 311*(5761), 622–627.
15. Nowack, B., & Bucheli, T. D. (2007). Occurrence, behavior and effects of nanoparticles in the environment. *Environmental Pollution, 150*(1), 5–22.
16. Klaine, S. J., Alvarez, P. J. J., Batley, G. E., et al. (2008). Nanomaterials in the environment: Behavior, fate, bioavailability, and effects. *Environmental Toxicology and Chemistry, 27*(9), 1825–1851.
17. Handy, R. D., von der Kammer, F., Lead, J. R., et al. (2008). The ecotoxicology and chemistry of manufactured nanoparticles. *Ecotoxicology, 17*(4), 287–314.
18. Navarro, E., Baun, A., Behra, R., et al. (2008). Environmental behavior and ecotoxicity of engineered nanoparticles to algae, plants, and fungi. *Ecotoxicology, 17*(5), 372–386.
19. Roco, M. C. (2003). Broader societal issues of nanotechnology. *Journal of Nanoparticle Research, 5*(3–4), 181–189.
20. National Research Council. (2004). *Nanoscale science and technology: Building a big future from small things*. National Academies Press.