ISSN 2616-5910 Vol. 6, Issue 1: 33-40, DOI: 10.25236/AJALS.2025.060105

Advances in Metallic Nano-Pesticides: Synthesis, Mechanisms, Applications, Safety, and Future Perspectives

Chu Wan[1, a], Shuquan Xin[1, b ,*], Xiaodan Li[2, c], Xinpei Wei[1, d], Jiangfeng Yang[1, e]

[1]*School of Life Science, Changchun Normal University, Changchun, 130032, China*
[2]*Dandong Customs Technology Center, Dandong, Liaoning, 118000, China*
[a]*wanchuccsf@163.com,* [b]*xinshuquan@ccsfu.edu.cn,* [c]*zhanglihui_91@163.com,* [d]*weixinpei@yeah.net,*
[e]*abcyjfdd@163.com*
**Corresponding author*

Abstract: *Metallic nano-pesticides have emerged as a promising technology in modern agriculture, offering improved efficacy, reduced environmental impact, and potential applications in precision agriculture. This review provides a comprehensive overview of metallic nano-pesticides, covering their synthesis methods, mechanisms of action, applications in pest and disease control, and ecological safety concerns. The synthesis section explores physical, chemical, and biological approaches, highlighting their respective advantages and limitations. The antimicrobial effects of metallic nanoparticles are analyzed in terms of their interaction with microbial membranes, ion release, and photocatalytic activity. Their applications as fungicides, insecticides, and herbicides are discussed, emphasizing their role in combating pesticide resistance and enhancing agricultural productivity. However, concerns regarding their environmental fate, bioaccumulation, and potential toxicity to soil microbiota and plants are critically examined. Finally, future perspectives on integrating nano-pesticides with smart agricultural technologies, risk assessment frameworks, and sustainable synthesis strategies are discussed, underscoring their potential to drive the transition toward eco-friendly and high-efficiency agricultural systems.*

Keywords: *Metallic nano-pesticides, Nanotechnology, Antimicrobial mechanism, Agricultural applications, Pesticide resistance*

1. Introduction

Since the 20th century, the global population has exhibited exponential growth, leading to an increasing demand for food, feed, fuel, and fiber[1]. Each year, plant diseases and pests cause global crop yield losses ranging from 20% to 40%. Pesticides, being inexpensive and available in diverse types, are crucial tools for guaranteeing global food production and security. Nevertheless, the long-term application of pesticides has led to the rise in the resistance of pests and pathogens to them, which in turn further exacerbates the reliance on pesticides[2]. Although the promotion of biopesticides has made progress in terms of environmental sustainability, challenges such as low utilization efficiency, complex active ingredients, and poor environmental stability persist. Additionally, the presence of 15%-30% organic solvents and surfactants in biopesticide formulations raises environmental concerns[3, 4]. Given the limitations of current pesticide formulation technologies and application practices, enhancing the utilization efficiency of active ingredients is considered one of the most effective strategies to reduce pesticide usage[5].

The rapid advancement of nanotechnology offers innovative solutions to challenges associated with conventional pesticide formulations and presents new opportunities for the development of nano-pesticides[6]. Nano-pesticides, an emerging technology in modern agriculture, contain active ingredients dispersed at nanoscale dimensions ranging from 1 to 300 nm. Due to their small size and high reactivity, nano-pesticides significantly improve bioavailability and efficacy in pest control. These novel formulations enhance pesticide stability and uniform dispersion, thereby reducing environmental pollution while increasing crop yield and quality[7]. Their high permeability and strong adhesion enable effective pest control even at lower dosages, mitigating resistance development and minimizing toxicity risks to humans. Moreover, nano-pesticides exhibit controlled-release properties, making them valuable tools for precision agriculture and sustainable farming. By improving pesticide efficiency and optimizing agricultural resource utilization, nano-pesticides contribute to enhancing agricultural productivity, protecting the environment, and promoting green agricultural development[8].

Metallic nanoparticles (MNPs), characterized by their heavy metal properties and exceptional physicochemical characteristics, exhibit strong antimicrobial toxicity. In recent years, MNPs have gained widespread applications in agricultural production and plant protection, becoming a research focus for crop disease management. These nanoparticles not only possess intrinsic antimicrobial properties but also induce physical and mechanical damage to pathogen cell structures and generate reactive oxygen species (ROS), ultimately leading to pathogen cell death and effectively suppressing resistance development. Furthermore, MNPs can enhance plant resistance and promote plant growth[9]. This review provides a comprehensive summary of metal nanoparticle preparation technologies, the mechanisms of metal-based nano-pesticides, their practical applications, and their environmental behavior and safety. Finally, the review discusses future prospects and challenges, aiming to provide a reference for the application of metal nanotechnology in agriculture.

2. Metallic Nanoparticle Synthesis

2.1 Physical Methods

The physical synthesis of metallic nanoparticles (MNPs) is characterized by its simplicity, high purity, and uniform particle size distribution. However, it requires high energy consumption, specialized and expensive equipment, and often results in low nanoparticle yield[10-12]. Common physical synthesis methods include laser ablation, evaporation-condensation, mechanical ball milling, and magnetron sputtering[13]. For example, Park et al. successfully synthesized metal and metal oxide nanoparticles on high-surface-area carbon materials (NP/C) using physical vapor deposition techniques[12]. Additionally, researchers have synthesized Ag nanoparticles of varying sizes on unheated substrates under different direct current (DC) magnetron sputtering conditions[10]. Bae et al. employed laser ablation (Nd: YAG, $\lambda=1064$ nm) using silver targets in different concentrations of sodium chloride ($NaCl_2$) solution. Their results showed that Ag nanoparticles produced in a 5 mM $NaCl_2$ solution exhibited a particle size distribution between 5 nm and 50 nm, with an average diameter of 26 nm[14].

2.2 Chemical Methods

Chemical synthesis methods, including solvent-based synthesis, sol-gel processing, electrochemical methods, and hydrothermal/organothermal techniques, have gained prominence due to their low energy requirements, rapid reactions, short synthesis time, high yield, and controllable particle size and morphology. These advantages make chemical synthesis one of the most widely used approaches for nanoparticle production. For instance, in the synthesis of gold nanoparticles (AuNPs), gold salts or acids serve as precursors, which are chemically reduced to metallic gold (Au^0) using reducing agents, while stabilizers are added to ensure particle stability[15, 16]. The sol-gel method is also extensively applied in the design and synthesis of metallic nanoparticles, including magnetic nanoparticle composites such as CoPt and FePt[17].

Table 1: Common metallic nanoparticle synthesis methods and their advantages/disadvantages.

Contrast	Physical method	Chemistry method	Biological method
Method	Laser ablation method Evaporative condensation method Mechanical ball milling method Magnetron sputtering method	Solvent method Sol-gel method Electrochemical process Hydrothermal/organic solvothermal method	Plant extract Microbial synthesis
Advantages	Can be suitable for mass production. Generate nanoparticles with uniform and controllable size and shape.		Simple Easy to expand culture (Plants)
Disadvantages	Processing equipment is expensive.	Chemical reagents are seriously polluted.	Not easy to expand culture (Microorganisms) Uneven shape and size

Despite the widespread use of physical and chemical methods for MNP synthesis, both approaches have limitations. Physical methods are costly and yield low production rates, whereas chemical methods often involve the use of organic solvents, acidic or alkaline solutions, and toxic reducing agents (e.g., sodium borohydride and hydrazine hydrate), which pose significant risks to human health and the environment. Additionally, these processes may generate hazardous byproducts. Table 1 summarizes the commonly used methods for metallic nanoparticle synthesis along with their advantages and disadvantages[11].

2.3 Biological Methods

Biological synthesis methods utilize biomolecules or natural substances to reduce metal precursors, producing nanoparticles in an eco-friendly manner without toxic chemical impurities. This method is cost-effective, sustainable, and safer for both humans and the environment[18]. Compared to nanoparticles produced via other methods, biologically synthesized nanoparticles exhibit superior antimicrobial and antioxidant properties while maintaining greater stability[19].

2.3.1 Phytosynthesis (Plant Extract-Based Synthesis)

Plant synthesis or plant extract-mediated synthesis is to extract bioactive compounds from various plant tissues (such as roots, stems, leaves and fruits), such as polyphenols, flavonoids, alkaloids and terpenoids[20-22], which are used as reducing agents and stabilizers in the formation of nanoparticles. Studies have shown that these natural organic molecules can directly promote the biosynthesis of MNP, and realize efficient and sustainable production of nanoparticles without exogenous surfactants[21]. The process is simple: the plant water extract is mixed with a metal salt solution in a controlled environment (for example, room temperature or mild heating), in which biologically active compounds reduce metal ions to form metal nanoparticles or metal oxide nanoparticles, as shown in Figure 1.

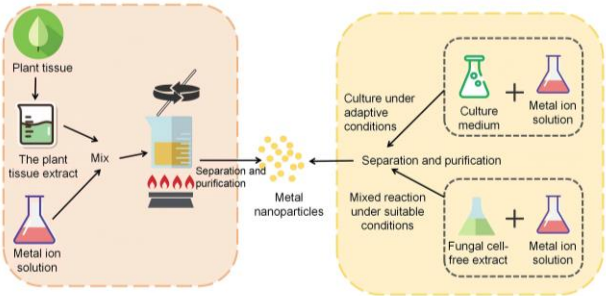

Figure 1: The biosynthesis process of metallic nanoparticles.

2.3.2 Microbial Synthesis

Microbial-mediated synthesis of metallic nanoparticles utilizes bacteria, actinomycetes, yeast, fungi, and algae as bioreductants or biocatalysts, as summarized in Table 2[20-22]. Metal ion precursors are added to the microbial culture medium, and microbial cells or their metabolites promote the reduction and chemical transformation of metal ions to produce metal nanoparticles (Figure 1). These metabolites can be used as stabilizers and surface modifiers to enhance the biocompatibility and new functions of synthetic nanoparticles.The microbial synthesis mechanism relies on metabolic activities and interactions between biomolecules and metal ions. Within or outside microbial cells, specific biomolecules recognize and bind metal ions, triggering redox reactions that convert them into metallic atoms. These atoms subsequently aggregate into nanoparticles, forming stable colloidal dispersions. Given its bio-friendly nature, microbial synthesis is gaining traction as a promising green alternative for MNP production.

Table 2: Microbial species used in metallic nanoparticle synthesis.

Microbial types	Synthetic strain	Nanoparticle
Bacteria	Cupriavidus metallidurans Bacillus subtilis 168 Halomonas salina Rhodopseudomonas capsulata Geobacillus Streptomyces	Au
	Bacillus methylotrophicus Streptomyces sp. LK3 Pseudomonas deceptionensis	Ag
	Lactobacillus plantarum VITES07 Bacillus megaterium cell	ZnO
	Shewanella oneidensis MR-1 Desulfovibrio desulfuricans	Pd
Actinomycetes	Arthrobacter nitroguajacolicus Streptomyces fulvissimus	Au

	Fusarium oxysporum Mariannaea sp.	
	Fusarium semitectum Volvariella volvacea	Ag
Yeasts	Saccharomyces cerevisiae Yeast extract peptone dextrose Yeast extract Saccharomyces cerevisiae	Ag
	Candida parapsilosis Magnusiomyces ingens LH-F1 Yarrowia lipolytica Saccharomyces cerevisiae	Au
	Marine yeast Pichia kudriavzevii	ZnO
Fungi	Aspergillus Aspergillus fumigatus	Zn
	Phanerochaete chrysosporium Aspergillus niger Periconium sp.	ZnO
	Morchella esculenta Fusarium solani Fusarium oxysporum	Au
	Pleurotus sp. Trichoderma harzianum Aspergillus sydowii Penicillium oxalicum Aspergillus fumigatus	Ag
Algae	Amphiroa rigida Chara vulgaris Padina sp Portieria hornemannii	Ag
	Gelidiella acerosa Sargassum crassifolium Cystoseira baccata	Au
	Tetraselmis indica Anabaena cylindrica Cladophora glomerata	ZnO
	Macrocystis pyrifera	CuO

3. Mechanism of Action of Metallic Nano-Pesticides

The antimicrobial effects of nanomaterials result from the complex interplay of their physical, chemical, and structural properties. Due to their small size and large specific surface area, metallic nanoparticles (MNPs) can interact closely with microbial cell membranes, leading to membrane penetration, structural damage, and eventual rupture. Additionally, the surface charge distribution of nanomaterials plays a critical role in disrupting microbial membrane integrity. Through electrostatic interactions, these materials destabilize cell membranes, inhibiting microbial growth and reproduction.

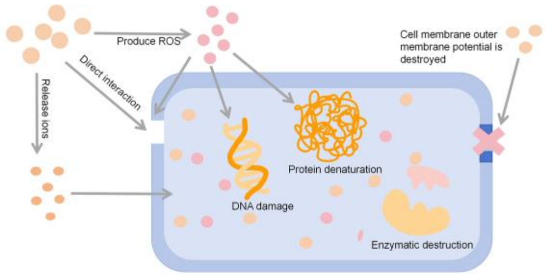

Figure 2: Mechanisms of action of metallic nanoparticles.

Metal nanoparticles also release metal ions, such as silver (Ag^+) and copper (Cu^{2+}), into aqueous environments, exhibiting significant antimicrobial activity against various microorganisms. These metal ions penetrate microbial cell membranes and react with intracellular proteins and enzymes, inhibiting essential biological activities and ultimately causing cell death. Moreover, under light exposure, certain nanomaterials generate photothermal effects or undergo photocatalytic reactions, producing heat or reactive oxygen species (ROS). These reaction products inflict additional damage on microbial cells, as illustrated in Figure 2.

4. Applications of Metallic Nano-Pesticides

4.1 Fungicides

The increasing resistance of bacteria and fungi to antimicrobial agents and antibiotics has created an urgent demand for novel fungicides. MNPs have demonstrated broad-spectrum antimicrobial activity against both Gram-positive and Gram-negative bacterial plant pathogens, such as *Xanthomonas translucens* and *Xanthomonas campestris*, as well as fungal pathogens like *Fusarium* and *Phytophthora* species[23, 24]. Comparative studies on cobalt ferrite ($CoFe_2O_4$) and nickel ferrite ($NiFe_2O_4$) nanoparticles have shown a reduction in *Fusarium* wilt incidence with minimal adverse effects on plant growth[25]. Additionally, silver nanoparticles (AgNPs) combined with *Ocimum sanctum* (holy basil) leaf extract exhibited enhanced antifungal activity against *Colletotrichum gloeosporioides*, a major pomegranate pathogen, compared to the leaf extract alone[26].

4.2 Insecticides

Synthetic insecticides remain a critical tool in controlling plant disease vectors; however, their adverse effects on non-target organisms and ecosystems, along with their potential for bioaccumulation and entry into the food chain, pose significant risks to human health and environmental safety[27]. Metallic nano-formulations offer several advantages over conventional insecticides, including reduced active ingredient usage, targeted action, and lower toxicity at effective doses, minimizing resistance development while maintaining eco-friendly characteristics[27-29].

Several metallic nanoparticles, such as Ag, silica (SiO_2), zinc oxide (ZnO), and copper oxide (CuO), have demonstrated promising insecticidal properties[30]. For instance, certain nano-insecticides exploit the inherent toxicity of MNPs; aluminum oxide (Al_2O_3) nanoparticles have shown great potential in controlling *Magnaporthe oryzae*, the causative agent of rice blast disease, during rice storage[31].

4.3 Herbicides

Most commercially available herbicides primarily target and eliminate the aerial parts of weeds. Unfortunately, they fail to effectively suppress underground structures such as rhizomes, bulbs, or tubers, which serve as sources for weed regrowth in subsequent seasons[32]. Nanotechnology enables the development of herbicides that selectively bind to plant-specific receptors, enhancing their efficacy by facilitating targeted entry and translocation to underground structures. This approach has the potential to disrupt glycolysis in weed root systems, thereby preventing energy storage and regrowth[32]. The application of metal nanoparticles in agriculture is shown in Figure 3.

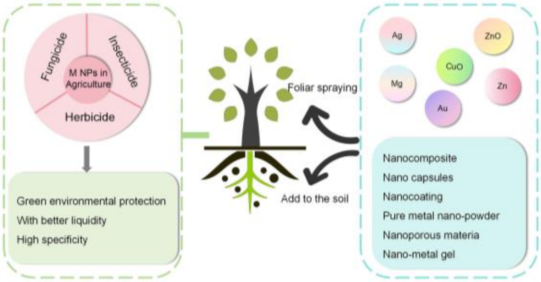

Figure 3: Applications of metallic nanoparticles in agriculture.

5. Safety Assessment of Metallic Nanoparticles

It is well recognized that nanoparticles present both benefits and potential risks to plants, soil, and human health. At certain concentrations, metal nanoparticles (MNPs) can adversely affect plant growth, making their phytotoxicity a critical area of research. The toxicity of nanomaterials is significantly influenced by particle size, crystalline structure, and other physicochemical properties. Prolonged agricultural application of MNPs may lead to their accumulation in soil and crops, potentially inducing soil toxicity and negatively impacting plant development[33].

For instance, titanium dioxide (TiO_2) exists in three mineral forms: anatase, brookite, and rutile, with anatase exhibiting the highest cytotoxicity, capable of inducing cell death and membrane rupture[34]. Studies have demonstrated that copper oxide (CuO) nanoparticles hinder seed development and pollen germination in various *Arabidopsis thaliana* ecotypes. Similarly, zinc (Zn) nanoparticles negatively affect plant biomass, with toxicity closely linked to their adsorption and uptake at the root surface, ultimately disrupting normal metabolic processes. Moreover, silver (Ag) nanoparticles have been shown to impair wheat (*Triticum aestivum*) growth by inhibiting root development and inducing abnormal physiological responses, thereby restricting overall plant vigor.

Despite their widespread use in antimicrobial applications, Ag nanoparticles raise concerns regarding environmental accumulation. As their usage continues to expand, the gradual buildup of nanoparticles in ecological systems may increase their presence in plant tissues, posing potential ecological risks. A systematic study on six higher plant species—radish (*Raphanus sativus*), oilseed rape (*Brassica napus*), ryegrass (*Lolium perenne*), lettuce (*Lactuca sativa*), maize (*Zea mays*), and cucumber (*Cucumis sativus*)—found that five types of tested nanoparticles exhibited significant inhibitory effects on seed germination and root growth. These findings provide crucial empirical evidence for evaluating the ecological safety of nanomaterials, underscoring the urgent need for comprehensive research on their environmental fate and biological impacts to ensure ecosystem stability and sustainable agricultural development[35].

In the context of soil pollution, microbial biomass serves as a vital indicator for assessing soil ecological health. Studies have shown that TiO_2 and CuO nanoparticles significantly reduce soil microbial biomass in submerged paddy soils, leading to decreased enzymatic activity and severe disruptions in microbial community structure. Additionally, excessive Fe_2O_3 nanoparticles drastically lower soil bacterial populations, altering microbial composition and ecological balance. Furthermore, ZnO and CeO_2 nanoparticles not only reduce the colony-forming ability of nitrogen-fixing bacteria, phosphorus-solubilizing bacteria, and potassium-solubilizing bacteria in culture media but also strongly inhibit key enzymatic activities, thereby severely impeding nutrient transformation and biogeochemical cycling in soil ecosystems[36].

6. Future Perspectives

As a promising technology for sustainable agriculture, metallic nano-pesticides are poised to benefit from interdisciplinary advancements in materials science and biology. Breakthroughs in green synthesis techniques will further promote environmentally friendly production processes, while the integration of precision agriculture technologies is expected to revolutionize conventional pesticide application methods. Smart management systems, incorporating IoT sensors and AI-driven algorithms, will enable real-time optimization of nano-pesticide spraying dosages. Additionally, drone-mounted nano-sprayers will enhance field application efficiency by precisely targeting disease hotspots.

However, large-scale application of metallic nano-pesticides faces challenges related to ecological safety and standardization. Establishing a globally unified risk assessment framework is crucial for systematically analyzing the long-term environmental fate and food chain transmission risks of nanomaterials. The development of a comprehensive life-cycle database and high-throughput toxicity screening platforms will be essential for evaluating their environmental impact. Although high production costs and limited public awareness currently hinder widespread adoption, advancements in cost-effective green synthesis methods and the implementation of eco-labeling systems will facilitate the large-scale commercialization of metallic nano-pesticides. Over the next decade, these innovations are expected to drive the transition toward high-efficiency, low-input, and ecologically compatible agricultural practices, solidifying metallic nano-pesticides as a key technology for the future of smart and sustainable agriculture.

In summary, the evolution of metallic nano-pesticides will be deeply embedded in the interdisciplinary landscape of materials science and biology. Major breakthroughs in green synthesis technologies will continue to advance environmentally friendly production processes, paving the way for the next generation of sustainable agricultural solutions.

Acknowledgements

Thanks to all those who contributed to the formation of the paper. This study was funded by Changchun Normal University graduate students' scientific research and innovation (YJSCX2024108).

References

[1] Xuejian, C., et al., Past, Present and Development Trend of Pesticide Formulations. modern agrochemicals, 2024. 23(05): p. 1-6.
[2] Qiuyu, X., et al., Research progress of nanomaterials based on pesticide application scenarios. Modern agrochemicals, 2024. 23(05): p. 17-23+31.
[3] Guoliang, Z., Discussion on the restrictive factors and countermeasures to improve the utilization efficiency of biological pesticides on fruit trees. Agriculture and technology, 2012. 32(05): p. 39-40.
[4] Jiadong, Z., Construction and application of lignosulfonate nano-pesticide. 2023, Zhejiang University: Zhejiang.
[5] Yueming, T., et al., Research progress of nano-pesticides. World pesticide, 2024. 46(03): p. 20-25.
[6] Huiping, C., et al., Research progress of nano-hygienic insecticides Pesticide. World pesticide, 2025: p. 1-8.
[7] Elmer, W. and J.C. White, The Future of Nanotechnology in Plant Pathology. Annual Review of Phytopathology, Vol 56, 2018. 56(1545-2107 (Electronic)): p. 111-133.
[8] Brunel, F., N.E. El Gueddari, and B.M.J.C.p. Moerschbacher, Complexation of copper (II) with chitosan nanogels: toward control of microbial growth. Carbohydr Polym, 2013. 92(2): p. 1348-1356.
[9] Ganlin, Study on the inhibitory effect of nano-silver materials on plant pathogenic bacteria. 2008, University of Agriculture and Forestry in Fujian: Fujian.
[10] Asanithi, P., S. Chaiyakun, and P.J.J.o.N. Limsuwan, Growth of silver nanoparticles by DC magnetron sputtering. Journal of Nanomaterials, 2012. 2012(1): p. 963609.
[11] Ovais, M., et al., Biosynthesis of metal nanoparticles via microbial enzymes: a mechanistic approach. International Journal of Molecular Sciences, 2018. 19(12): p. 4100.
[12] Park, H.-Y., et al., Green synthesis of carbon-supported nanoparticle catalysts by physical vapor deposition on soluble powder substrates. Scientific Reports, 2015. 5(1): p. 14245.
[13] Ruihua, D., Study on Green Synthesis of Metal Nanoparticles from Ginkgo biloba Extract and Its Application. 2023, Lanzhou university of technology: Lanzhou.
[14] Tien, D.-C., et al., Discovery of ionic silver in silver nanoparticle suspension fabricated by arc discharge method. Journal of Alloys and Compounds, 2008. 463(1-2): p. 408-411.
[15] Ledwith, D.M., A.M. Whelan, and J.M.J.J.o.M.C. Kelly, A rapid, straight-forward method for controlling the morphology of stable silver nanoparticles. Journal of Materials Chemistry, 2007. 17(23): p. 2459-2464.
[16] Li, X., et al., Facile synthesis of silver nanoparticles with high concentration via a CTAB-induced silver mirror reaction. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2012. 400: p. 73-79.
[17] Qingqing, W., et al., Research progress in design and preparation of metal and alloy nano-materials by sol-gel method, Acta Physico-Chimica Sinica, 2019. 35(11): p. 1186-1206.
[18] Yanbin, H., Study on synthesis and application of copper nanosheets at atmospheric pressure, in Beijing University of Chemical Technology 2024, Beijing University of Chemical Technology: Beijing.
[19] Kimta, N., et al., Applications of Pteridophytes in Nanotechnology: a class that has not yet explored to the extent of its potential. Green Chemistry Letters and Reviews, 2025. 18(1): p. 2460641.
[20] Hano, C. and B.H.J.B. Abbasi, Plant-based green synthesis of nanoparticles: Production, characterization and applications. 2022, Multidisciplinary Digital Publishing Institute. p. 31.
[21] Narayanan, K.B., N.J.A.i.c. Sakthivel, and i. science, Green synthesis of biogenic metal nanoparticles by terrestrial and aquatic phototrophic and heterotrophic eukaryotes and biocompatible agents. Advances in Colloid and Interface Science, 2011. 169(2): p. 59-79.
[22] Tolaymat, T.M., et al., An evidence-based environmental perspective of manufactured silver nanoparticle in syntheses and applications: a systematic review and critical appraisal of peer-reviewed scientific papers. Science of The Total Environment, 2010. 408(5): p. 999-1006.
[23] Esteban-Tejeda, L., et al., Antibacterial and antifungal activity of a soda-lime glass containing copper nanoparticles. Nanotechnology, 2009. 20(50): p. 505701.
[24] Giannousi, K., et al., Selective synthesis of Cu2O and Cu/Cu2O NPs: antifungal activity to yeast Saccharomyces cerevisiae and DNA interaction. Inorganic Chemistry, 2014. 53(18): p. 9657-9666.
[25] Sharma, P., et al., Nanomaterial fungicides: in vitro and in vivo antimycotic activity of cobalt and

nickel nanoferrites on phytopathogenic fungi. Global Challenges, 2017. 1(9): p. 1700041.
[26] Sherkhane, A., et al., Control of bacterial blight disease of pomegranate using silver nanoparticles. Journal of a Nanomedicine & Nanotechnology, 2018. 9(3): p. 500.
[27] Li, X., et al., Advanced nanopesticides: Advantage and action mechanisms. Plant Physiology and Biochemistry, 2023. 203: p. 108051.
[28] Kah, M., et al., Nanopesticides: state of knowledge, environmental fate, and exposure modeling. Critical Reviews In Environmental Science and Technology,2013. 43(16): p. 1823-1867.
[29] Kah, M. and T.J.E.i. Hofmann, Nanopesticide research: current trends and future priorities. Environment International, 2014. 63: p. 224-235.
[30] Deka, B., et al., Nanopesticides: a systematic review of their prospects with special reference to tea pest management. Front Nutr, 2021. 8: p. 686131.
[31] Das, S., A. Yadav, and N.J.J.o.S.P.R. Debnath, Entomotoxic efficacy of aluminium oxide, titanium dioxide and zinc oxide nanoparticles against Sitophilus oryzae (L.): A comparative analysis. Journal of Stored Products Research, 2019. 83: p. 92-96.
[32] Acharya, A. and P.K.J.N. Pal, Agriculture nanotechnology: Translating research outcome to field applications by influencing environmental sustainability. Nano Impact, 2020. 19: p. 100232.
[33] Rajput, V.D., et al., Nano-enabled products: challenges and opportunities for sustainable agriculture. Plants, 2021. 10(12): p. 2727.
[34] Singh, R.P., R. Handa, and G.J.J.o.c.r. Manchanda, Nanoparticles in sustainable agriculture: An emerging opportunity. Journal of Controlled Release, 2021. 329: p. 1234-1248.
[35] Ahmad, A., et al., Influence of metallic, metallic oxide, and organic nanoparticles on plant physiology. Chemosphere, 2022. 290: p. 133329.
[36] Rajput, V.D., et al., Effect of nanoparticles on crops and soil microbial communities. Journal of Soils and Sediments, 2018. 18: p. 2179-2187.