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# Green Synthesized Nanoparticles in Agriculture: A Sustainable Approach for Enhanced Crop Protection and Soil Health – A Review

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**Abstract**

Nanotechnology application in agriculture has also proved to be an effective means to promote sustainable crop protection and soil health. Plant extract, microbe, and biopolymer derived green-synthesized nanoparticles (NPs) provide a novel, green substitute for the synthetic agrochemicals currently being used. Recent progress in green NP synthesis, characterization, and their uses in agriculture has been discussed here with special emphasis on their use for pest control, disease suppression, and nutrient delivery. The antimicrobial and pesticidal activity of metal and metal oxide NPs, including silver (AgNPs), zinc oxide (ZnO NPs), and copper (Cu NPs), has shown marked effectiveness against phytopathogens with minimum environmental toxicity. In addition, green NPs enhance soil fertility through increased microbial activity, nutrient supply, and water holding capacity, sustaining agricultural production. Their biocompatibility and biodegradability decrease the potential for bioaccumulation and render them a less harmful choice compared to synthetic pesticides. Nonetheless, issues like scalability, regulatory, and toxicity need closer examination. This review is a thorough evaluation of the mechanism, advantages, and future outlook of green-synthesized NPs in agriculture with a view to closing the gap between nanotechnology and sustainable agriculture.

**Keywords:** Biopolymer; Characterization; Nutrient Delivery; Pest Control; Soil Fertility

## 1. Introduction

Nanoscience and nanotechnology have emerged as revolutionary fields in the past few decades, significantly impacting various domains, including medicine, electronics, environmental remediation, and agriculture. The unique physicochemical properties of nanoparticles (NPs), such as high surface area-to-volume ratio, tunable optical and electrical characteristics, and enhanced reactivity, make them highly beneficial in numerous applications[1] . The synthesis and application of NPs have provided innovative solutions to longstanding challenges, particularly in agricultural sustainability, where they play a crucial role in enhancing crop protection and soil health. However, the conventional methods of nanoparticle synthesis, including chemical and physical approaches, pose environmental and economic concerns, leading to an increasing interest in green synthesis techniques that leverage biological entities such as plants, bacteria, and fungi for eco-friendly nanoparticle production.

Nanoparticles can be synthesized via various approaches categorized into physical, chemical, and biological methods. Physical methods, such as laser ablation, ball milling, and sputtering, are widely used but require high energy inputs and sophisticated equipment, making them costly and environmentally challenging[2]. Chemical methods, including co-precipitation, sol-gel, and hydrothermal techniques, often involve hazardous reagents that generate toxic by-products, raising concerns regarding environmental safety and sustainability[3] . In contrast, green synthesis methods utilize biological systems such as plant extracts, microorganisms, and biomolecules as reducing and stabilizing agents, offering an eco-friendly and cost-effective alternative[4]**.** These green methods not only reduce the toxicity associated with chemical synthesis but also enhance the biocompatibility of the nanoparticles, making them highly suitable for agricultural applications[5].

The applications of nanoparticles span across multiple fields, including medicine, where they are employed in targeted drug delivery and imaging; environmental science, where they aid in pollution control and water purification; and electronics, where they contribute to the development of high-performance materials and devices[6]. In agriculture, nanoparticles have shown remarkable potential in improving crop yield, pest control, soil remediation, and nutrient management. The integration of nanotechnology in agriculture has led to the development of nano-fertilizers, nano-pesticides, and nano-sensors, which enhance nutrient uptake efficiency, provide controlled pesticide release, and facilitate real-time monitoring of soil and plant health.

A detailed examination of nanoparticle applications in agriculture reveals their pivotal role in addressing critical challenges such as pest infestation, soil degradation, and nutrient loss. Nano-fertilizers, for instance, improve the bioavailability of essential nutrients like nitrogen, phosphorus, and potassium, reducing the dependency on conventional fertilizers and minimizing environmental pollution[7]. Similarly, nano-pesticides enhance the efficiency of pest control by providing targeted and sustained release of active ingredients, thereby reducing the overall pesticide load and mitigating adverse effects on non-target organisms[8]. Furthermore, nano-sensors embedded in agricultural systems enable real-time detection of soil moisture, nutrient levels, and pathogen presence, facilitating precision farming and optimizing resource utilization[9]. The use of green-synthesized nanoparticles in these applications offers a sustainable and eco-friendly approach to modernizing agriculture, ensuring food security while maintaining environmental integrity.

## 2. Green Synthesis of Metal/Metal Oxide Nanoparticles from Bio Extracts

Green synthesis of metal and metal oxide nanoparticles has gained significant attention due to its eco-friendly, cost-effective, and sustainable nature. This approach utilizes plant extracts, microorganisms, and other biological sources as reducing and stabilizing agents to synthesize nanoparticles under mild reaction conditions. The general procedure involves preparing an aqueous or ethanolic extract of a biological source, followed by mixing it with a metal precursor solution (e.g., $AgNO_3$ for silver nanoparticles or $Zn(NO_3)_2$ for ZnO nanoparticles). The reaction is typically carried out at room temperature or with mild heating, leading to the bioreduction of metal ions and the stabilization of nanoparticles by biomolecules present in the extract.

The mechanism of green synthesis primarily involves phytochemicals such as flavonoids, alkaloids, terpenoids, polyphenols, and proteins acting as reducing agents. These biomolecules donate electrons to metal ions, reducing them to their respective zero-valent or oxide forms. Additionally, the functional groups present in biomolecules stabilize the nanoparticles, preventing aggregation. For example, Madhuca indica flower extract has been reported to facilitate the synthesis of PdNPs through polyphenolic compounds acting as reducing and capping agents[10]. Similarly, green tea (Camellia sinensis) extract has been used for the biosynthesis of gold nanoparticles due to its rich flavonoid content[11]. Metal oxide nanoparticles, such as ZnO and $TiO_2$, have also been synthesized using plant extracts, demonstrating enhanced antimicrobial and catalytic properties.

## 3. Characterization Methods of Nanoparticles and Their Applications

Characterization of nanoparticles is crucial for understanding their structural, morphological, and functional properties, which influence their applications in various fields. The key characterization techniques include: UV-Visible Spectroscopy Used for the optical analysis of nanoparticles, especially metal nanoparticles, by identifying surface plasmon resonance (SPR) peaks. Fourier Transform Infrared Spectroscopy (FTIR) – Determines the functional groups involved in nanoparticle stabilization and capping. X-ray Diffraction (XRD) – Provides information on the crystalline nature, phase composition, and average crystallite size. Scanning Electron Microscopy (SEM) – Analyzes the surface morphology, shape, and size of nanoparticles. Transmission Electron Microscopy (TEM) – Offers high-resolution imaging to determine nanoparticle size, shape, and dispersion. Dynamic Light Scattering (DLS) – Measures hydrodynamic size and polydispersity index, essential for understanding colloidal stability. Zeta Potential Analysis – Assesses the surface charge, which indicates nanoparticle stability in suspension. Energy Dispersive X-ray Spectroscopy (EDS or EDAX) – Confirms the elemental composition of nanoparticles. X-ray Photoelectron Spectroscopy (XPS) – Identifies oxidation states and surface chemical composition. These characterization techniques are essential for optimizing nanoparticles for applications in medicine, agriculture, catalysis, and environmental remediation. For instance, well-characterized ZnO and AgNPs are widely used in antimicrobial coatings, drug delivery, and plant disease management due to their controlled size and stability.

## 4. Applications of Green Synthesized Nanoparticles in Crop Protection and Yield Enhancement

Green-synthesized nanoparticles have emerged as promising tools for sustainable agriculture, offering eco-friendly alternatives to conventional pesticides and fertilizers. These biologically derived nanoparticles enhance plant growth, improve resistance to pathogens, and increase nutrient availability, ultimately leading to better crop yield and protection. Various plant-based NPs, such as AgNPs, ZnO NPs, and $Fe_3O_4$ NPs, have been extensively studied for their agricultural applications. The applications of green-synthesized nanoparticles in agriculture highlight their potential in sustainable crop production. They enhance plant growth, improve stress tolerance, and provide effective disease control, making them a viable alternative to conventional agrochemicals. The use of plant-based nanoparticles not only reduces environmental toxicity but also contributes to eco-friendly and efficient farming practices. Green synthesized NPs have emerged as a sustainable solution for enhancing agricultural productivity by improving crop protection and yield. These nanoparticles, synthesized using plant extracts and microorganisms, exhibit antimicrobial, antifungal, and growth-promoting properties, reducing the need for chemical pesticides and fertilizers. The controlled release of nutrients and active compounds from nanoparticles ensures efficient uptake by plants, minimizing environmental pollution and enhancing crop resilience.

Silver nanoparticles synthesized from Azadirachta indica[12] leaf extract have demonstrated significant antifungal activity against plant pathogens, including Fusarium oxysporum and Alternaria solani[13], which cause wilt and early blight in crops like tomato and potato. Similarly, ZnO NPs derived from Ocimum sanctum[14] (Holy Basil) have been reported to enhance seed germination and plant growth in wheat by improving nutrient absorption and chlorophyll synthesis. $Fe_3O_4$ NPs synthesized using Moringa oleifera extract have shown potential as nano-fertilizers, significantly increasing root length and biomass in maize and riceyoun[15]. Apart from their antimicrobial and fertilization effects, green synthesized nanoparticles are also effective in pest control. Copper nanoparticles produced using Allium sativum (Garlic) extract ranahave exhibited strong insecticidal activity against Spodoptera litura, a major pest affecting soybean and cotton crops[16]. Additionally, silica-based nanoparticles derived from Cymbopogon citratus (Lemongrass) have been used to enhance plant defense mechanisms in rice, reducing damage from bacterial leaf blight[17].

## 5. Applications of Green Synthesized Nanoparticles in Soil Health

Green synthesized nanoparticles (NPs) play a crucial role in improving soil health by enhancing soil fertility, nutrient availability, microbial activity, and contaminant remediation. These nanoparticles, derived from plant and microbial extracts, provide sustainable solutions for soil amendments, reducing the dependence on chemical fertilizers and improving crop productivity. Various metal and metal oxide nanoparticles have been studied for their positive impact on soil health, ensuring long-term agricultural sustainability.

CuO NPs derived from Azadirachta indica extract have been utilized to improve soil enzyme activity[18] and suppress soil-borne pathogens in tomato crops. AgNPs synthesized using Allium sativum extract have shown potential in mitigating soil-borne fungal infections, enhancing root health in soybean[19]. Magnesium oxide nanoparticles (MgO NPs) obtained from Cymbopogon citratus extract have been used to neutralize acidic soils, improving pH balance and nutrient uptake in rice[20]. $TiO_2$ NPs synthesized from Aloe vera have demonstrated increased soil water retention, improving moisture availability for drought-prone crops such as sorghum[21].

Nanoparticles also play a role in heavy metal remediation and soil detoxification. Green synthesized iron nanoparticles from Withania somnifera have been effective in removing arsenic contamination from paddy fields[22], while manganese oxide nanoparticles from Trigonella foenum-graecum have facilitated lead removal from contaminated soils in lettuce cultivation[23]. Additionally, cerium oxide nanoparticles from Curcuma longa have been utilized for phosphorus retention, improving soil fertility in potato farming[24].

## 6. Conclusion

Green synthesized nanoparticles have emerged as a sustainable and eco-friendly alternative to conventional agrochemicals, offering significant benefits in crop protection and soil health management. Their biocompatibility, non-toxic nature, and enhanced efficiency make them promising candidates for improving plant growth, pest control, and soil fertility while minimizing environmental risks. Various metal and metal oxide nanoparticles synthesized using plant extracts have demonstrated antimicrobial, pesticidal, and nutrient-enhancing properties, contributing to increased crop yield and soil sustainability. Additionally, their role in heavy metal remediation and soil detoxification highlights their potential in sustainable agricultural practices. Despite these advantages, challenges such as large-scale production, stability, and regulatory concerns must be addressed to facilitate their widespread adoption. Further research is needed to optimize synthesis methods, assess long-term ecological impacts, and develop cost-effective formulations suitable for agricultural applications. Integrating green nanotechnology with precision farming and organic agriculture can lead to innovative solutions for food security and environmental sustainability. By replacing synthetic agrochemicals with bio-inspired nanomaterials, green synthesized nanoparticles hold immense potential in revolutionizing modern agriculture while preserving natural resources.

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