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Silver Nanoparticles (Ag-NPs) as Nanoparticles for Sustainable Cotton Crop Protection

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Abstract
Silver nanoparticles (Ag-NPs) have gained tremendous attention in recent years due to their exceptional antimicrobial, catalytic, and biocompatible properties. This review highlights the synthesis, characterization, and applications of Ag-NPs in sustainable cotton crop protection. The review emphasizes the mechanisms of pathogen inhibition, environmental benefits, and potential challenges associated with nanoparticle-based agriculture. Through a systematic analysis of global studies (2020–2025), it is evident that Ag-NPs can serve as a sustainable alternative to conventional pesticides, offering eco-friendly and effective protection against bacterial and fungal infections in cotton. The paper concludes with recommendations for safe deployment and future research prospects.

Keywords
Silver nanoparticles, Cotton crop, Green synthesis, Nanotechnology, Sustainable agriculture, Pathogen inhibition

1. Introduction

Nanotechnology has emerged as a transformative tool for sustainable agriculture. Among the various nanomaterials, silver nanoparticles (Ag-NPs) have demonstrated potent antimicrobial properties and are being increasingly applied in crop protection systems. Cotton, being one of the world's most important fiber crops, is frequently affected by bacterial blight, boll rot, and fungal wilt diseases. Conventional pesticides, although effective, cause environmental pollution, resistance development, and toxicity to non-target species. Therefore, the integration of Ag-NPs offers a promising approach to minimize these drawbacks while maintaining crop health and yield.

2. Synthesis and Characterization of Silver Nanoparticles

Ag-NPs can be synthesized through physical, chemical, and biological routes. Green synthesis using plant extracts, bacteria, and fungi has gained momentum due to its environmental friendliness and cost-effectiveness. In particular, Neem (Azadirachta indica), Aloe vera, and Tulsi extracts are frequently used as reducing and capping agents. Characterization techniques such as UV-Vis spectroscopy, scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR) confirm the size, shape, and crystallinity of Ag-NPs. Typically, biosynthesized Ag-NPs exhibit a surface plasmon resonance peak between 400–430 nm and particle sizes ranging from 10 to 50 nm.

3. Mechanism of Ag-NPs in Cotton Crop Protection

Ag-NPs exhibit antimicrobial action through multiple mechanisms: (1) disruption of microbial cell membranes, (2) generation of reactive oxygen species (ROS), (3) interference with DNA replication, and

(4) inhibition of essential enzymes. In cotton, these mechanisms collectively reduce the severity of diseases such as Xanthomonas campestris-induced blight and Fusarium wilt. Ag-NPs can also enhance plant defense enzymes, including peroxidase and catalase, strengthening the plant's immune response.

4. Review of Recent Global Research (2020–2025)

Several studies have investigated the application of Ag-NPs in cotton and other crops. Singh and Kumar (2024) demonstrated that biosynthesized Ag-NPs reduced cotton leaf blight by 35% without phytotoxic effects. Patel et al. (2023) reported improved soil microbial balance when Ag-NPs were applied in microdoses. Zhao and Gupta (2022) discussed the synergistic use of Ag-NPs with biopolymers for slow release in soil, enhancing long-term crop protection. Khan (2021) highlighted the low eco-toxicity of green-synthesized Ag-NPs compared to chemically synthesized ones. These findings collectively suggest that Ag-NPs are a viable component of next-generation nano-enabled agriculture.

5. Environmental and Economic Perspectives

While Ag-NPs provide significant benefits, their environmental impact must be carefully managed. Excessive accumulation of nanoparticles in soil and water can alter microbial diversity. However, studies show that biologically synthesized Ag-NPs degrade faster and exhibit lower toxicity. Economically, Ag-NP-based formulations are cost-competitive when produced at scale using green synthesis. Their efficiency in reducing pesticide usage can lower overall cultivation costs for farmers.

6. Challenges and Future Prospects

Despite their promise, several challenges hinder the commercial adoption of Ag-NPs in agriculture. Regulatory frameworks for nanomaterials remain inconsistent across countries. Long-term ecological studies are still limited, and standardization of nanoparticle dosage and delivery mechanisms is essential. Future research should focus on large-scale field trials, bio-degradability studies, and the development of composite nanomaterials with enhanced selectivity and minimal environmental footprint.

7. Conclusion

Silver nanoparticles represent a transformative innovation in sustainable cotton crop protection. They offer an effective, environmentally friendly, and economically viable alternative to synthetic pesticides. This review establishes that controlled use of Ag-NPs can improve crop health, enhance disease resistance, and contribute toward achieving global sustainability goals. Continued interdisciplinary research combining nanotechnology, plant science, and environmental safety is essential to ensure responsible application of these advanced materials in modern agriculture.

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Conflict of Interest

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Author Contributions

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