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Green-Synthesized Metal Oxide Nanoparticles in Post-Harvest Disease Management and Quality Enhancement of Fruits: A Review

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Post-harvest losses of fruits due to fungal pathogens and physiological deterioration pose a major challenge to global food security. Conventional chemical fungicides, though effective, raise concerns regarding environmental safety, residue toxicity, and pathogen resistance. In recent years, nanotechnology has emerged as a promising alternative, particularly the use of green-synthesized metal oxide nanoparticles. Plant-mediated synthesis of nanoparticles offers an eco-friendly, cost-effective, and sustainable approach with enhanced antimicrobial efficacy. Among these, copper oxide nanoparticles (CuO NPs) synthesized using botanical extracts such as *Azadirachta indica* have shown remarkable antifungal activity and potential in extending shelf life while maintaining fruit quality. This review summarizes recent advances in green synthesis of metal oxide nanoparticles, their mechanisms of action against post-harvest pathogens, applications in fruit preservation, effects on physicochemical quality parameters, and safety aspects. The review highlights the potential of nanoparticle-based strategies as sustainable tools for post-harvest disease management and quality enhancement in fruits.

Keywords: Green synthesis, copper oxide nanoparticles, post-harvest disease, fruit quality, antifungal activity, nanotechnology

Introduction

Post-harvest losses account for nearly 20–30 % of total fruit production worldwide, mainly due to fungal diseases, moisture loss, and rapid ripening. Pathogens such as *Colletotrichum*, *Aspergillus*, *Penicillium*, and *Botrytis* significantly reduce fruit quality and market value. The excessive use of chemical fungicides has resulted in residue accumulation, environmental pollution, and health hazards, necessitating safer alternatives (Rai *et. al.*, 2016). Nanotechnology offers novel solutions in agriculture and food preservation. Metal oxide nanoparticles, due to their small size, large surface area, and enhanced reactivity, have shown strong antimicrobial properties. Green synthesis using plant extracts has gained attention as it avoids toxic chemicals and improves biocompatibility, making nanoparticles suitable for post-harvest applications.

Green synthesis of metal oxide nanoparticles

Green synthesis involves the use of plant extracts, microorganisms, or biopolymers as reducing and stabilizing agents. Plant-based synthesis is preferred due to its simplicity, scalability, and eco-friendliness. Phytochemicals such as flavonoids, phenolics, terpenoids, and alkaloids play a crucial role in nanoparticle formation and stabilization (Singh et al., 2016). Among various metal oxides, copper oxide nanoparticles have attracted significant interest because copper is an essential micronutrient and exhibits strong antifungal activity. *Azadirachta indica* (neem) leaf extract is widely used owing to its antimicrobial and antioxidant properties, which enhance the stability and bioactivity of synthesized nanoparticles (Kumar and Yadav, 2009). In nanoparticle biosynthesis, maintaining consistent particle size, stable structure, and uniform dispersion in solution is often difficult. These challenges can be minimized by proper control of synthesis conditions, particularly pH, temperature, and incubation time.

Antifungal mechanism of nanoparticles

Metal oxide nanoparticles inhibit fungal growth through multiple mechanisms:

- Disruption of fungal cell wall and membrane integrity
- Generation of reactive oxygen species (ROS) leading to oxidative stress
- Interaction with fungal enzymes and DNA
- Inhibition of spore germination and mycelial growth

These multi-target actions reduce the chances of resistance development compared to conventional fungicides.

Application in post-harvest disease management

Green-synthesized nanoparticles have been successfully applied through fruit dipping, coating, and spraying methods (Joshi et al., 2025). Studies have reported significant reduction in disease incidence caused by *Colletotrichum gloeosporioides*, *Aspergillus niger*, and *Penicillium* species in mango, citrus, apple, and banana. Copper oxide nanoparticles, when applied at optimized concentrations, effectively control anthracnose and other post-harvest diseases while being safe for fruit tissues. Their prolonged antimicrobial activity contributes to extended storage life.

Effect on fruit quality parameters

In addition to disease control, nanoparticle treatments positively influence fruit quality attributes:

- Reduced physiological weight loss
- Maintenance of firmness
- Delayed ripening and respiration rate
- Higher retention of ascorbic acid
- Balanced total soluble solids and titratable acidity

These effects collectively contribute to improved shelf life and consumer acceptability of treated fruits.

Safety and environmental considerations

Although nanoparticles are highly effective, their safety is a critical concern. Green-synthesized nanoparticles are generally less toxic due to the absence of harmful chemicals. Studies indicate that copper residues in treated fruits remain within permissible limits when applied at recommended concentrations. However, long-term environmental impact and human health risk assessments are necessary before large-scale commercialization.

Future prospects

Future research should focus on:

- Optimization of nanoparticle dosage and application methods
- Development of nanoparticle-based edible coatings
- Field-level validation and commercialization
- Comprehensive toxicological and regulatory studies

Integration of nanotechnology with sustainable post-harvest management practices holds great promise for reducing food losses.

Conclusion

Green-synthesized metal oxide nanoparticles represent a sustainable and effective alternative to chemical fungicides for post-harvest disease management. Copper oxide nanoparticles synthesized using plant extracts such as *Azadirachta indica* exhibit strong antifungal activity and significantly enhance fruit shelf life and quality. Their eco-friendly nature, combined with multifunctional benefits, makes them promising candidates for future post-harvest technologies. Nevertheless, further research on safety, standardization, and large-scale application is essential to ensure their successful adoption in the food supply chain.

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