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Antibacterial Coatings for Maintaining Fruit Quality

*B. Pawan Kumar and Dr. D. Naga Harshitha
Sri Konda Laxman Telangana State Horticultural University, India
*Corresponding Author's email: boyinapawan@gmail.com

Microbial contamination is a primary factor contributing to postharvest fruit deterioration. Antibacterial edible coatings, particularly those composed of biodegradable polymers functionalized with natural or inorganic antimicrobial agents, have gained attention as sustainable alternatives to conventional preservation techniques. This review summarizes current advances in antibacterial coatings for fruit preservation, focusing on material composition, mechanisms of microbial inhibition, physicochemical effects on fruit quality, and safety considerations. Special emphasis is placed on chitosan-based matrices, essential oil nanoemulsions, and zinc oxide nanoparticles as synergistic agents for quality maintenance and microbial control.

Keywords: Antibacterial coatings; Chitosan; Essential oils; Zinc oxide nanoparticles; Fruit quality; Postharvest preservation

Introduction

Postharvest loss of fruits and vegetables accounts for approximately 20–30% of total production worldwide (Sivakumar *et al.*, 2021). These losses result primarily from microbial decay, respiration-driven senescence, and moisture loss during storage and transportation. Conventional preservation approaches—refrigeration, controlled atmosphere storage, or synthetic fungicides—are only partially effective and raise environmental or health concerns (Blancas-Benítez *et al.*, 2022). In recent years, antibacterial edible coatings have emerged as a promising approach to preserve fruit quality. These coatings form a semi-permeable film over the fruit surface, controlling gas exchange and moisture diffusion while simultaneously inhibiting microbial growth. The development of such multifunctional coatings integrates materials science, microbiology, and food technology (Basumatary *et al.*, 2021).

Composition and Functional Mechanisms of Antibacterial Coatings

Biopolymer-based coatings are primarily derived from polysaccharides (e.g., chitosan, starch, alginate, cellulose derivatives) and proteins (e.g., gelatin, soy, casein). Chitosan, a deacetylated derivative of chitin, exhibits intrinsic antimicrobial activity due to its cationic amino groups, which interact electrostatically with negatively charged microbial membranes, leading to leakage of intracellular constituents (Basumatary *et al.*, 2021). Essential oils and plant extracts provide natural antimicrobial and antioxidant activities, while metal nanoparticles such as ZnO or Ag add potent antibacterial activity through ROS generation and ion release (La *et al*., 2021).

Mechanism of Quality Preservation

The efficacy of antibacterial coatings derives from synergistic mechanisms involving barrier effects, antimicrobial action, antioxidant protection, and moisture regulation. Reduced gas permeability slows respiration and ethylene biosynthesis, while antimicrobial compounds directly inhibit microbial metabolism (Ma et al., 2024). The coatings also preserve antioxidants and prevent enzymatic browning (Blancas-Benítez *et al.*, 2022).

Method for Coating Assessment and efficacy

A representative chitosan–ZnO system can be prepared by dissolving 1.0% (w/v) chitosan in 1% acetic acid, adding 0.5% glycerol, and incorporating 0.3% ZnO nanoparticles by sonication. Fruits are dipped for 2–3 min, air-dried, and stored at 4–10°C. Parameters such as microbial count, weight loss, firmness, and antioxidant activity are monitored periodically.

Chitosan–cinnamon oil coatings suppressed mold growth by 2 log CFU g^{-1} in strawberries (Blancas-Benítez et al., 2022). Chitosan–ZnO coatings reduced fungal decay in apples by 70% (La *et al.,* 2021). These studies confirm that antibacterial coatings extend shelf life and maintain sensory quality.

Potential migration of nanoparticles and volatile residues necessitates toxicological evaluation. ZnO and TiO_2 nanoparticles are recognized as safe at ≤0.5% (w/v) concentrations (La *et al.,* 2021). Essential oil dosages must be optimized to avoid aroma alterations (Basumatary *et al.,* 2021). Emerging research focuses on smart coatings with freshness indicators, biopolymer recycling, and predictive modeling for performance optimization (Ma *et al.,* 2024).

Composition and Functional Mechanisms

Chitosan-based coatings

Chitosan is a cationic polysaccharide obtained from chitin (e.g., shrimp shell waste) with intrinsic antimicrobial activity. It interacts with microbial cell membranes via electrostatic forces, leading to leakage of intracellular materials and cell death (Basumatary *et al.*, 2021)

Additionally, chitosan forms clear, flexible films that adhere well to fruit surfaces and slow respiration rates.

Example:

Strawberries coated with 1% chitosan solution maintained visual quality and reduced total aerobic counts by 2 log CFU/g compared with uncoated fruits during 12 days at 4 °C (Blancas-Benítez et al., 2022).

The coating also reduced weight loss by 45%, delayed surface mold growth, and maintained higher firmness (approximately 75% of initial value).

Mechanism Explanation

Chitosan's amino groups (–NH_2) protonate under acidic conditions, forming NH_3^+ groups that bind to negatively charged microbial surfaces. This destabilizes the cell membrane and interferes with nutrient transport, leading to antimicrobial activity.

Essential oil-incorporated coatings

Essential oils (EOs) such as cinnamon oil, thyme oil, or clove oil are rich in phenolic compounds like eugenol, thymol, and cinnamaldehyde, which disrupt microbial cell walls and inhibit enzymes.

However, due to volatility and odour intensity, EOs are typically added in nano emulsified form, allowing controlled release and minimizing sensory impact.

Example:

Apple slices coated with chitosan–cinnamon oil (0.2% v/v) showed a 70% reduction in fungal infection by *Penicillium expansum* and maintained 90% firmness after 14 days at 10 °C (La *et al.*, 2021).

The combination of the chitosan matrix (barrier) and cinnamon oil (antimicrobial) produced synergistic inhibition against both bacteria and fungi.

Mechanism Explanation

Cinnamaldehyde and eugenol penetrate microbial membranes, altering permeability and causing leakage of proteins and electrolytes. Nanoencapsulation provides a steady release of these compounds at low concentrations, prolonging antimicrobial effects over time.

Metal oxide nanoparticle coatings

Nanoparticles such as ZnO, TiO_2, and Ag have been integrated into edible coatings to achieve strong, long-lasting antimicrobial action. ZnO nanoparticles are especially favored due to

their GRAS status, UV protection, and ability to produce reactive oxygen species (ROS) that oxidize microbial membranes (La *et al.*, 2021).

Example:

Mangoes coated with chitosan–ZnO nanocomposite (0.3% ZnO) displayed reduced total microbial load by 3 log CFU/g and delayed ripening by 6 days compared with uncoated fruit (Ma et al., 2024).

The coating preserved color (L* value), maintained soluble solids, and prevented the rapid softening commonly seen during tropical fruit storage.

Mechanism Explanation

ZnO nanoparticles release Zn^{2+} ions and generate ROS (H_2O_2, O_2^-, OH^- radicals) that damage microbial DNA and cell membranes. When embedded in chitosan, these nanoparticles are stabilized and evenly distributed, ensuring sustained antimicrobial activity.

Composite coatings

Blending polymers improves coating performance. For example, combining chitosan (antimicrobial) with beeswax (moisture barrier) creates a dual-function coating with both gas and water resistance.

Citrus fruits coated with chitosan–beeswax composite showed 40% lower weight loss and maintained higher ascorbic acid content than uncoated controls after 20 days (Xing *et al.*, 2019).

Mechanistic Basis of Quality Preservation

Antibacterial coatings preserve fruit quality via four key mechanisms:

1. Barrier control – limits O_2 and CO_2 transmission, slowing respiration and ethylene biosynthesis.
2. Microbial inhibition – direct interaction with microbial membranes or oxidative stress induction.
3. Antioxidant protection – EOs and phenolic compounds scavenge free radicals, reducing enzymatic browning.
4. Moisture retention – reduced transpiration prevents shriveling and weight loss.

Conclusion

Antibacterial coatings are a validated, sustainable approach for prolonging fruit shelf life. Combining natural polymers with bioactive agents enhances microbial inhibition and preserves physicochemical properties. Further research should address scale-up, safety, and regulatory validation for commercial adoption.

References

1. Basumatary, I. B., Sahoo, G., & Sahu, S. K. (2021). Chitosan-based antimicrobial coating for improving postharvest quality of fruits. Coatings, 11(6), 736.
2. Blancas-Benítez, F. J., Sánchez-Ortiz, A., Contreras-Padilla, M., & Pérez-Flores, J. (2022). Impact of edible coatings on quality of fruits: A review. Food Chemistry Advances, 2, 100116.
3. La, D. D., Nguyen, D. T., & Park, S. Y. (2021). Effects of zinc oxide nanoparticles incorporated in edible coatings on fruit preservation and microbial inhibition. LWT – Food Science and Technology, 147, 111651.
4. Ma, M., Zhou, X., Li, J., & Chen, H. (2024). Edible coatings for fresh-cut fruits and vegetables: Mechanisms and recent advances. Postharvest Biology and Technology, 211, 112088.
5. Sivakumar, D., Williams, C., & Korsten, L. (2021). Edible coatings to maintain fruit quality: A comprehensive review. Frontiers in Microbiology, 12, 667274.
6. Xing, Y., Xu, Q., Yang, H., Liu, X., & Li, X. (2019). Antimicrobial nanoparticles incorporated in edible coatings for fruit preservation. Molecules, 24(10), 1883.