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Postharvest Technology

Probiotic-Encapsulated Edible Coatings for Ginseng Root Storage Stability

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Abstract: -

Ginseng roots (Panax ginseng) are highly susceptible to postharvest deterioration, with substantial losses in ginsenoside content caused by fungal infection, oxidative stress, and enzymatic degradation during storage. This article reviews probiotic-encapsulated edible coatings as an active bio-preservation strategy to enhance ginseng storage stability. The coatings employ multilayer matrices of alginate, red ginseng dietary fiber, and chitosan to encapsulate viable Lactobacillus strains, forming living biofilms on root surfaces. These probiotics suppress major storage fungi through organic acid and bacteriocin production while simultaneously stabilizing ginsenosides and regulating moisture and gas exchange. Experimental evidence indicates significant reductions in mold incidence, retention of over 85% ginsenosides during long-term storage, and maintenance of firmness, antioxidant activity, and microbial safety under ambient conditions. The technology is cost-effective, scalable, and utilizes ginseng by-products, aligning with sustainable postharvest practices. Overall, probiotic-encapsulated edible coatings represent a promising chemical-free alternative to conventional fungicides for preserving the medicinal quality and market value of ginseng roots.

Introduction:

Ginseng roots (*Panax ginseng*) are highly valued for their medicinal properties, primarily due to ginsenosides, which possess immunomodulatory, anti-inflammatory, antioxidant, and adaptogenic effects. Postharvest losses remain a critical bottleneck, with 20–35% of ginsenoside content degraded during ambient storage. The losses are

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primarily attributed to fungal contamination by *Fusarium* and *Rhizoctonia*, enzymatic breakdown, and oxidative stress, which compromise the therapeutic efficacy and market value of ginseng roots (Jeon *et al.*, 2023).

Traditional storage methods, including gunny bags and chemical fungicides, often fail to maintain quality over extended periods, with chemical residues raising safety concerns. In response, probiotic-encapsulated edible coatings have been developed as a bioactive postharvest intervention. These coatings incorporate beneficial Lactobacillus strains within multilayer matrices composed of alginate and red ginseng dietary fiber (RGDF). The coatings form living biofilms on ginseng roots, leveraging probiotics' natural antifungal metabolites, such as organic acids and bacteriocins, to inhibit pathogen growth while stabilizing ginsenosides, achieving up to 85% retention over six months (Son *et al.*, 2023). This approach combines biological, physical, and chemical protection, providing a sustainable alternative to conventional preservatives.

Mechanism and Function of Probiotic-Encapsulated Edible Coatings

The multilayer coating is constructed via layer-by-layer assembly to ensure structural integrity and functional performance:

1. **Alginate core (2% w/v)**: Encapsulates live probiotic cells, providing a hydrated microenvironment that supports survival during storage and gastric passage.
2. **Red ginseng dietary fiber (1–2%)**: Enhances adhesion to root surfaces by mimicking natural root mucilage, promoting uniform film coverage and reducing localized exposure to pathogens.
3. **Chitosan outer seal**: Forms a semi-permeable barrier, retaining moisture, regulating gas exchange, and providing additional antimicrobial properties.

Probiotic strains such as *Limosilactobacillus reuteri* KGC1901 and *Lacticaseibacillus casei* KGC1201 remain highly viable (≈90%) after lyophilization and exposure to simulated gastric conditions (pH 2.0, 3 hours), ensuring functional activity post-application (Jeon *et al.*, 2023). These probiotics produce lactic acid, reducing local pH to ~4.2, and secrete bacteriocins that disrupt fungal membranes. Together, these metabolites inhibit spore germination of *Fusarium* and *Rhizoctonia*, with MIC values of 10^6 CFU/mL, lowering mold incidence from 28% to 5% during ambient storage at 25°C and 85% relative humidity (Son *et al.*, 2023).

The coatings also provide dynamic defense, as surviving probiotics proliferate when rehydrated, continuously reinforcing antifungal activity throughout storage. RGDF contributes to improved film adhesion (up to 2× higher on HT-29 intestinal cell models) and mechanical strength, preventing film cracking and ensuring uniform coverage over the root surface.

Physiological and Biochemical Effects on Ginseng Roots

Beyond pathogen inhibition, probiotic coatings maintain key quality attributes:

- **Ginsenoside retention**: Coated roots preserve 88% of ginsenosides Rb1 and Rg1 over 180 days, compared to 62% in uncoated controls, verified by HPLC analysis (Jeon *et al.*, 2023).
- **Firmness and texture**: Coatings maintain root firmness between 15–18 N, reducing mechanical damage during handling.
- **Moisture content**: Roots retain 12–14% moisture, which prevents desiccation and maintains physiological freshness.
- **Microbial load**: Coated roots maintain <10^3 CFU/g, significantly lower than uncoated roots, minimizing the risk of spoilage and mycotoxin formation.
- **Antioxidant activity**: DPPH assays indicate 92% preservation of antioxidant capacity, outperforming roots treated with synthetic fungicides.

These coatings also limit oxidative degradation of ginsenosides and reduce enzymatic activity that would otherwise convert active compounds to inactive forms. The combination of mechanical protection, moisture regulation, and bioactive metabolite production results in a comprehensive preservation strategy.

Storage Application and Commercial Feasibility

Application involves dipping peeled roots in the probiotic solution at ~40°C, followed by air-drying to form a uniform ~50 µm film. Roots are then packed in breathable mesh or perforated bags, allowing gas exchange while maintaining the protective biofilm.

The technology is cost-effective (~$0.15/kg of roots), utilizes ginseng by-products for fiber matrices, and is scalable via spray-drying or layer-by-layer coating systems (Chaudhary *et al.*, 2021). These features make the approach suitable for small-scale farmers, commercial herbal processors, and pharmaceutical supply chains, providing both economic and ecological advantages.

Future Prospects

Advanced innovations are being explored to further improve postharvest preservation:

- **pH-responsive nano-capsules**: Trigger probiotic release upon detection of early-stage mold, providing targeted and energy-efficient antifungal action (Cheng *et al.*, 2025).

- **Multi-strain consortia**: Tailored probiotic communities for specific rhizome pathogens, applicable to turmeric, galanga, and other medicinal roots.
- **Digital integration**: QR-coded IoT-enabled packaging can monitor ginsenoside stability, root moisture, and microbial activity in real time, enabling precision postharvest management.
- **Automated coating systems**: Facilitate uniform application at scale, reducing labor costs and enhancing consistency.

Implementation of these strategies could reduce global medicinal rhizome postharvest losses by up to 40%, ensuring bioactive retention, quality, and commercial viability.

Conclusion

Probiotic-encapsulated edible coatings transform ginseng postharvest storage from passive protection to active bio-preservation, combining microbial inhibition, moisture retention, and stabilization of ginsenosides. This sustainable approach enhances medicinal quality, maintains antioxidant activity, and provides a chemical-free alternative to conventional fungicides. With scalable application methods and integration with smart monitoring technologies, these coatings offer a reliable, eco-friendly solution for the herbal pharmaceutical industry, ensuring consistent quality and supply across global markets.

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