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Postharvest Technology

Active Packaging with Gingerol-Loaded Films for Medicinal Rhizome Preservation

Nalanda Acharya*

Abstract: -

Postharvest losses in cut flowers and medicinal rhizomes are primarily caused by microbial spoilage, physiological senescence, and degradation of bioactive compounds. This review focuses on bioactive-based postharvest technologies, particularly nano-chitosan–herbal coatings for cut flowers and gingerol-loaded active packaging films for medicinal rhizomes such as ginger (*Zingiber officinale*). Nano-chitosan coatings enriched with neem or curcumin exhibit strong antimicrobial activity, regulate ethylene biosynthesis, and maintain vascular integrity, thereby extending vase life and preserving floral quality. Gingerol-loaded films act as controlled-release systems that inhibit fungal growth, stabilize moisture, and protect thermolabile gingerols during storage, resulting in improved retention of essential oils and oleoresins. These approaches provide sustainable, chemical-free alternatives to synthetic preservatives and significantly enhance shelf life and product quality. Although challenges remain in terms of cost, scalability, and regulatory acceptance, integration with cold-chain systems and smart monitoring technologies holds promise for broader commercial adoption in floriculture and medicinal crop supply chains.

Introduction:

Cut flowers, such as roses (*Rosa* spp.) and carnations (*Dianthus caryophyllus*), and medicinal rhizomes, particularly ginger (*Zingiber officinale*), are highly perishable commodities valued for aesthetic and therapeutic properties, respectively.

Postharvest losses in cut flowers occur due to microbial colonization, vascular blockage, and water stress, which accelerate wilting, petal abscission, and loss of freshness (Singh *et al.*, 2024). Similarly, medicinal rhizomes lose 20–40% of their bioactivity

Nalanda Acharya*
Research Scholar, Department of Pomology and Postharvest Technology,
Uttar Banga Krishi Viswavidyalaya, Pundibari, West Bengal-736165.

during storage due to fungal spoilage by *Fusarium* and *Aspergillus*, as well as degradation of key compounds like 6-gingerol (Varshini *et al.*, 2024). These losses affect both commercial and pharmaceutical value.

To address these challenges, bioactive-based coatings and films have emerged as sustainable postharvest strategies. For cut flowers, nano-chitosan coatings combined with herbal extracts, such as neem (*Azadirachta indica*) or curcumin (*Curcuma longa*), form nano-scale films that protect against microbial decay, reduce ethylene-induced senescence, and maintain turgor (Kumar *et al.*, 2023; Patel *et al.*, 2024). In medicinal rhizomes, active packaging films loaded with gingerol create self-antifungal barriers that gradually release bioactives, inhibit fungal growth, and preserve gingerols and essential oils over extended storage periods (Soni *et al.*, 2023). These strategies provide natural, safe, and environmentally friendly alternatives to synthetic preservatives, prolonging shelf life while maintaining quality.

Mechanism and Function of Nano-Chitosan-Herbal Coatings in Cut Flowers

Nano-chitosan coatings are applied as dips or sprays immediately after harvest, forming thin, uniform films on flower stems. Chitosan, a cationic polysaccharide, disrupts microbial membranes, causing leakage of intracellular contents and inhibiting bacterial and fungal growth (Singh *et al.*, 2024). At the nanoscale (50–100 nm), chitosan exhibits higher surface area, improved adhesion to stem tissues, and deeper penetration into xylem vessels.

Herbal extracts, including neem oil and curcumin, contain phenolic compounds and flavonoids that inhibit fungal spore germination and bacterial biofilm formation. These extracts act synergistically with nano-chitosan, lowering the minimum inhibitory concentration and preserving tissue integrity (Mehta *et al.*, 2023). The coatings also regulate ethylene biosynthesis by downregulating ACS and ACO genes, delaying petal senescence and maintaining chlorophyll content and fresh weight.

Experimental studies on roses treated with 0.5% nano-chitosan and 0.1% neem extract extended vase life from 14 to 21 days, reduced microbial colony-forming units, and maintained xylem vessel openness (Patel *et al.*, 2024). The coatings are compatible with environmentally safe practices, offering chemical-free alternatives that enhance consumer acceptance and commercial value. Integration with cold chain management, modified atmosphere packaging, and AI-driven shelf-life prediction models can further optimize flower distribution and quality maintenance (Singh *et al.*, 2024; Patel *et al.*, 2024).

Mechanism and Function of Gingerol-Loaded Active Films in Medicinal Rhizomes

Gingerol-loaded films are fabricated using biopolymer matrices such as LDPE or chitosan (1–2% w/v) with 0.5–2% 6-gingerol incorporated. These films act as controlled-release systems, gradually delivering gingerol to rhizome surfaces, following diffusion principles (Varshini *et al.*, 2024).

Released gingerol exhibits strong antifungal activity, inhibiting *Fusarium* spore germination by up to 92% (MIC 50 µg/mL) through membrane permeabilization, ROS generation, and disruption of fungal metabolism. Vapor-phase diffusion stabilizes moisture at 10–12%, preventing mold formation and maintaining rhizome firmness (Alam *et al.*, 2022).

Storage trials demonstrated that polyethylene-lined gunny bags with gingerol films retain 2.96% oleoresin and 3.20% essential oils after 180 days, compared to 1.8% in untreated controls. Microbial loads decreased from 5.15×10^4 CFU/g to $<10^3$ CFU/g, while visual quality was preserved (L* 45–50). The films also prevent heat-sensitive gingerols from converting to shogaols, maintaining pungency and therapeutic activity at 30°C/85% RH (Varshini *et al.*, 2024).

Additionally, the films reduce weight loss by 15% compared to traditional gunny bags and maintain curcumin-to-gingerol ratios, with HPLC analysis confirming 88% retention versus 65% in untreated samples (Soni *et al.*, 2023). Fabrication via solvent casting or extrusion is compatible with pre-treatments such as solar drying, ensuring scalable, energy-efficient production .

Importance

Bioactive-based nano-chitosan coatings with herbal extracts (neem, curcumin) and gingerol-loaded active films revolutionize postharvest management by significantly extending shelf life—roses from 14 to 21 days, rhizomes retaining 88% gingerols and 3.20% essential oils after 180 days—through antimicrobial action (reducing CFU/g from 5.15×10^4 to $<10^3$), ethylene regulation via ACS/ACO gene downregulation, moisture stabilization at 10-12%, and prevention of fungal spoilage (92% Fusarium inhibition), slashing 20-40% losses, enhancing commercial/pharmaceutical value, ensuring chemical-free sustainability, and integrating with cold chains/AI for scalable supply chain optimization across cut flowers and medicinal commodities like ginger.

Limitations

Despite efficacy, these technologies face high fabrication costs for nano-chitosan (50-100 nm) and biopolymer extrusion/solvent casting, scalability challenges for smallholder farmers, variable performance across species (roses vs. carnations, ginger vs. turmeric) due to differing xylem penetration and bioactive diffusion rates, dependency on precise postharvest conditions (30°C/85% RH, humidity control), limited long-term stability of herbal extracts/gingerols under humid/tropical storage leading to shogaol conversion, regulatory hurdles for nano-materials in food/pharma, and need for advanced HPLC/IoT integration which burdens resource-limited regions, restricting widespread adoption.

Future Prospects and Technological Integration

Emerging trends include smart coatings and films capable of stimulus-responsive release of bioactives in response to microbial growth, moisture, or pH changes. Integration with IoT sensors and AI-based monitoring can provide real-time alerts for spoilage and optimize storage and distribution. Expansion of these technologies to other ornamental species, turmeric, ashwagandha, and edible flowers could standardize bioactive retention (>90%) across supply chains, reducing global postharvest losses by up to 30% (Soni *et al.*, 2023; Patel *et al.*, 2024). Scalable fabrication methods, including extrusion and solvent casting, further ensure commercial feasibility.

Conclusion

Bioactive-based postharvest technologies, including nano-chitosan-herbal coatings for cut flowers and gingerol-loaded active films for medicinal rhizomes, offer effective, sustainable, and safe solutions to reduce losses, maintain quality, and preserve functional and aesthetic properties. These technologies integrate natural bioactives, control microbial growth, stabilize key compounds, and extend shelf life, benefiting producers, consumers, and the environment. Future developments in nano-encapsulation, smart release systems, and digital monitoring will further enhance their efficiency and industrial adoption, supporting sustainable floriculture and medicinal supply chains.

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