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Application of Waxing and Surface Coatings for Prolonging the Shelf Life of Citrus Fruits

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Fruits constitute an indispensable component of the human diet due to their rich composition of carbohydrates, dietary fiber, vitamins, minerals, antioxidants, flavonoids, and other health-promoting phytochemicals. Regular consumption of fruits has been strongly associated with reduced risk of chronic diseases such as cardiovascular disorders, diabetes, obesity, and certain cancers (Mares-Perlman et al., 2002). These nutritional and therapeutic benefits underline the growing global demand for fresh fruits, thereby necessitating not only increased production but also improved postharvest handling and quality preservation strategies.

Among horticultural commodities, fruits are highly perishable owing to their elevated moisture content, often exceeding 75%, coupled with active metabolic processes after harvest. Only about 30% of fruits produced globally reach consumers in acceptable condition, while the remaining proportion is lost due to improper postharvest management. The magnitude of these losses is particularly alarming in developing and underdeveloped countries, where inadequate infrastructure, poor storage facilities, and limited access to modern preservation technologies exacerbate postharvest deterioration (Pulamte, 2008). These losses represent not only economic setbacks for farmers and traders but also a significant waste of nutritional resources.

Fruit perishability is closely linked to the physiological and biochemical changes occurring during ripening and senescence. Based on ripening behavior, fruits are classified as climacteric and non-climacteric. Climacteric fruits such as mango, banana, apple, and papaya exhibit a pronounced rise in respiration rate and ethylene production after harvest, which accelerates ripening and senescence. In contrast, non-climacteric fruits like citrus, grapes, and strawberries do not show such a respiratory burst and generally cease ripening once harvested. The continuous ripening of climacteric fruits postharvest increases their susceptibility to microbial infection, mechanical damage, and physiological disorders, thereby limiting their shelf life.

Low-temperature storage has long been employed as a primary method to slow metabolic activity, enzymatic reactions, and ethylene synthesis in fruits. However, many tropical and subtropical fruits are highly sensitive to chilling injury when exposed to temperatures below their critical threshold. Symptoms such as surface pitting, browning, off-flavors, and increased susceptibility to decay severely compromise fruit quality (Patel et al., 2016). Therefore, alternative or complementary preservation strategies are essential to overcome the limitations associated with conventional cold storage.

In this context, edible surface coatings and waxing have emerged as promising postharvest technologies for extending the shelf life of fruit crops. Edible coatings are thin layers of edible materials applied directly to the fruit surface, forming a semi-permeable barrier that modulates gas exchange, reduces moisture loss, delays respiration, and inhibits microbial growth. Unlike synthetic packaging materials, edible coatings are biodegradable, environmentally friendly, and safe for human consumption.

Edible coatings are primarily formulated using biopolymers such as polysaccharides, proteins, lipids, or their combinations. Each class of coating material offers distinct functional properties. Lipid-based coatings and natural waxes effectively reduce water vapor transmission due to their hydrophobic nature, whereas polysaccharide-based coatings provide superior gas barrier properties. Protein-based coatings exhibit excellent mechanical strength and film-forming ability (Hassan et al., 2018). Plasticizers, emulsifiers, and resins are commonly incorporated into coating formulations to enhance flexibility, adhesion, and structural stability.

Beyond their physical barrier function, edible coatings serve as carriers for active compounds, including antimicrobials, antioxidants, essential oils, probiotics, and nanoparticles. Incorporation of such bioactive agents enables the development of active coatings capable of suppressing postharvest pathogens, delaying oxidative processes, and improving nutritional quality. Recent advancements in nanotechnology and controlled-release systems have further expanded the functional potential of edible coatings in fruit preservation.

From a commercial perspective, waxing and surface coatings play a critical role in maintaining fruit appearance, reducing postharvest losses, and meeting market and export standards. Natural waxes such as carnauba wax, shellac, and beeswax have long been used in the fruit industry to enhance gloss and delay dehydration, particularly in citrus and apple fruits. Modern edible coatings aim to go beyond cosmetic enhancement by providing multifunctional protection while aligning with sustainability and food safety requirements.

This review comprehensively examines the application of waxing and edible surface coatings for prolonging the shelf life of fruit crops. It discusses the physiological basis of fruit ripening, types and characteristics of coating materials, application technologies, incorporation of active additives, and practical applications in major fruit crops. Recent innovations, limitations, and future research directions are also highlighted to provide a holistic understanding of this evolving postharvest technology.

Postharvest Losses in Fruit Crops: Global and Indian Perspective

Postharvest losses in fruit crops represent a major challenge to global food security, nutritional availability, and farm income. Fruits are highly perishable commodities due to their high moisture content, soft texture, and continued metabolic activity after harvest. Globally, postharvest losses of fruits and vegetables are estimated to range between 20–40%, with even higher losses reported in developing countries where infrastructure for storage, transportation, and cold chain management remains inadequate (Kader, 2005). These losses translate into substantial economic damage and reduced availability of nutritionally rich foods. In India, postharvest losses are particularly severe owing to fragmented supply chains, inadequate cold storage capacity, poor packaging practices, and limited adoption of modern postharvest technologies.

Physiology of Fruit Ripening and Senescence

Fruit ripening is a genetically programmed, irreversible physiological process involving a series of biochemical and structural changes that transform immature fruits into edible products with desirable color, texture, flavor, and aroma. Senescence follows ripening and is characterized by cellular degradation, membrane disintegration, and increased susceptibility to microbial infection. These processes continue even after harvest, making postharvest management critically important (Chen et al., 2020).

Ripening involves coordinated changes in respiration rate, ethylene biosynthesis, carbohydrate metabolism, pigment transformation, cell wall modification, and volatile compound production. At the molecular level, ripening is regulated by complex transcriptional networks and signaling pathways that respond to hormonal and environmental cues. Once senescence sets in, irreversible quality deterioration occurs, leading to softening, browning, off-flavors, and decay.

Climacteric and Non-Climacteric Fruits

Fruits are broadly classified into climacteric and non-climacteric categories based on their ripening behavior. Climacteric fruits such as mango, banana, apple, and papaya exhibit a distinct surge in respiration and ethylene production at the onset of ripening. This ethylene burst acts as a key regulator, accelerating biochemical changes associated with softening, sugar accumulation, and aroma development (Farcuh et al., 2018). In contrast, non-climacteric fruits such as citrus, grapes, strawberries, and cherries do not show a postharvest respiratory peak and produce minimal ethylene. These fruits generally do not ripen further once harvested and are more dependent on preharvest maturity for quality development. Nevertheless, non-climacteric fruits remain susceptible to dehydration, chilling injury, and fungal decay during storage. Understanding these physiological differences is crucial for designing appropriate postharvest interventions such as edible coatings and waxing.

Role of Ethylene and Respiration

Ethylene is a pivotal plant hormone regulating fruit ripening, senescence, and abscission. In climacteric fruits, ethylene biosynthesis is autocatalytic, meaning that small amounts of ethylene stimulate further production, rapidly advancing ripening processes (Chen et al., 2020). Elevated respiration rates during ripening lead to faster depletion of stored substrates and increased heat production, accelerating senescence. Manipulation of ethylene action and respiration through physical barriers, temperature management, and atmospheric modification is a widely adopted postharvest strategy. Edible coatings and surface waxing play a significant role by creating semi-permeable barriers that restrict oxygen ingress and carbon dioxide efflux, thereby lowering respiration rates and delaying ethylene-mediated ripening.

Concept of Waxing and Edible Surface Coatings

Edible surface coatings are thin layers of edible material applied directly to the surface of fruits to enhance shelf life and maintain quality. These coatings act as protective barriers that regulate gas exchange, reduce moisture loss, and protect against mechanical damage and microbial invasion. Unlike synthetic packaging, edible coatings are biodegradable, environmentally friendly, and safe for human consumption.

Definition and Historical Background

The use of surface coatings on fruits dates back several centuries, when natural waxes were applied to citrus fruits in China to prevent dehydration and enhance visual appeal. Over time, the practice evolved into commercial waxing using shellac, carnauba wax, and beeswax, particularly for apples and citrus fruits (Beyza et al., 2018). Modern edible coatings are designed not only to improve appearance but also to actively extend shelf life through functional and bioactive components.

Waxing versus Edible Coatings

Waxing traditionally refers to the application of hydrophobic lipid-based materials that primarily reduce moisture loss and enhance gloss. While effective in limiting transpiration, waxes may sometimes excessively restrict gas exchange, leading to anaerobic respiration and off-flavor development if improperly applied. Edible coatings, in contrast, are formulated using polysaccharides, proteins, lipids, or their composites, offering tunable permeability to gases and water vapor. These coatings can be engineered to carry antimicrobial agents, antioxidants, and nanoparticles, making them multifunctional preservation systems rather than passive barriers.

Types of Waxing and Coating Materials

Polysaccharide-Based Coatings

Polysaccharide-based coatings derived from starch, cellulose, chitosan, alginate, pectin, and gums are widely used due to their excellent film-forming ability and gas barrier properties. These coatings effectively reduce oxygen diffusion, thereby lowering respiration rates and delaying ripening. However, their hydrophilic nature often results in high water vapor permeability, necessitating blending with lipids or crosslinking agents to improve moisture resistance.

Protein-Based Coatings

Protein-based coatings such as gelatin, whey protein, casein, soy protein, and zein provide superior mechanical strength and elasticity. These coatings form cohesive networks that offer moderate gas and moisture barrier properties. Protein films can be modified through enzymatic or chemical crosslinking to enhance structural stability and functional performance.

Lipid-Based Coatings and Natural Waxes

Lipid-based coatings, including beeswax, carnauba wax, shellac, and fatty acids, are highly effective in reducing moisture loss due to their hydrophobic nature. These coatings are particularly beneficial for fruits prone to dehydration, such as citrus and apples. However, lipid coatings alone often exhibit poor mechanical strength and limited gas permeability control

Composite and Multilayer Coatings

Composite coatings combine polysaccharides, proteins, and lipids to achieve balanced barrier properties. Multilayer and layer-by-layer coatings further enhance functionality by allowing sequential deposition of different materials, improving mechanical strength, controlled release of bioactives, and overall coating performance.

Functional Properties and Characterization of Edible Coatings

The effectiveness of edible coatings depends on their physical, mechanical, and barrier properties, including thickness, permeability to gases and water vapor, tensile strength, adhesion, and optical clarity. Advanced analytical techniques such as scanning electron microscopy, atomic force microscopy, and permeability testing are used to characterize coating structure and performance. Optimized coatings maintain fruit firmness, color, nutritional quality, and sensory attributes during storage (Falguera et al., 2011).

Application Technologies of Waxing and Coatings

Edible coatings can be applied using dipping, spraying, brushing, atomization, or electrospraying techniques. Each method influences coating uniformity, thickness, and material utilization. Spray and electrospray techniques offer precise control and reduced coating material wastage, making them suitable for industrial-scale applications.

Role of Active Additives in Coatings

Antimicrobial Agents

Incorporation of natural antimicrobials such as chitosan, essential oils, peptides, and biocontrol microorganisms enhances the ability of coatings to suppress postharvest pathogens. These active coatings effectively reduce fungal decay and extend storage life without relying on synthetic fungicides.

Antioxidants and Essential Oils

Antioxidants and essential oils incorporated into coatings delay oxidative browning, preserve phenolic compounds, and improve sensory quality. Controlled release of these compounds ensures prolonged protection during storage.

Nanomaterials and Nano-Coatings

Nanotechnology has enabled the development of nano-enhanced edible coatings with improved barrier properties and antimicrobial efficacy. Nanoparticles such as ZnO, nanoclays, and nanoemulsions enhance coating functionality while reducing material usage (Hasan et al., 2020).

Application of Waxing and Coatings in Major Fruit Crops

Edible coatings have demonstrated significant benefits in mango, citrus, banana, apple, berries, and exotic fruits by delaying ripening, reducing weight loss, maintaining firmness, and controlling microbial spoilage (Mendy et al., 2019).

Integration of Edible Coatings with MAP and CA Storage

Combining edible coatings with modified atmosphere packaging and controlled atmosphere storage synergistically enhances shelf life by regulating gas composition and reducing physiological stress (Kanellis et al., 2009).

Advantages

- **Reduces Moisture Loss:** Acts as a hydrophobic barrier, preventing wilting and shriveling, preserving firmness and weight.
- **Slows Respiration:** Creates a diffusion barrier, limiting oxygen intake and carbon dioxide release, thereby slowing the ripening and aging process.
- **Inhibits Microbial Growth:** Protects against fungal and bacterial pathogens by sealing cracks and creating a non-conducive surface.
- **Enhances Appearance:** Provides a glossy, shiny finish, increasing visual appeal and consumer acceptance.
- **Controls Browning & Spoilage:** Reduces enzymatic browning and chilling injury, preserving color and texture.
- **Carrier for Additives:** Can deliver antimicrobials, antioxidants, or sprout inhibitors, enhancing preservation.
- **Cost-Effective:** Can be cheaper than refrigerated storage for reducing spoilage.

Limitations

- **Gas Exchange Issues:** Poorly formulated or overly thick coatings can restrict oxygen too much, leading to anaerobic respiration, off-flavors (like ethanol), and physiological disorders.
- **Affects Natural Ripening:** Can interfere with normal ripening processes, causing issues like blotchy ripening or poor texture development.
- **Regulatory Complexities:** Ingredients and formulations must comply with food laws (e.g., FDA, EU), which vary by region and fruit type.
- **Potential Allergens:** Some coating components or additives can cause allergic reactions.
- **Not a Cure-All:** Effectiveness depends on the specific fruit, coating type, and storage conditions; might not always match controlled atmosphere storage.

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