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REVIEW ARTICLE

Wax coating technology for post-harvest quality preservation in vegetable: Mechanisms, applications and advances

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Abstract

Post-harvest losses in fresh vegetables significantly affect quality, shelf life and market value, especially in tropical and subtropical regions where high temperature and humidity accelerate deterioration. Wax coating has emerged as a simple, economical and effective post-harvest technology for extending the storage life of vegetables. Fresh vegetables naturally possess a thin epicuticular wax layer that regulates transpiration and respiration; however, this protective barrier is often reduced during harvesting, washing, grading and handling operations. The application of edible wax coatings helps restore this protective layer by forming a semi-permeable film on the surface of the produce. This coating reduces physiological loss in weight by minimising moisture loss, delays respiration and senescence, maintains firmness and improves gloss and appearance, thereby enhancing market acceptability. Various food-grade waxes such as shellac, carnauba wax, paraffin wax, polyethylene wax and blended wax emulsions are widely used, either individually or in combination, depending on the commodity and storage conditions. The effectiveness of wax coating depends on wax type, concentration and application methods such as dipping, spraying, foam application, flooding and roller brushing. Optimal coating concentration is essential because excessive coating may restrict gas exchange and lead to anaerobic respiration and off-flavour development. Recent advances include biodegradable coatings, composite edible films and nano-based coatings with improved barrier and antimicrobial properties. Future research should emphasise eco-friendly, residue-free coatings and commodity-specific formulations. Overall, wax coating is an efficient post-harvest strategy for reducing losses, extending shelf life and improving the quality and marketability of fresh vegetables.

Keywords: edible wax coating; fresh vegetables; moisture loss; post-harvest management; quality maintenance; respiration rate; shelf life extension; wax concentration

Introduction

Vegetable crops are highly perishable commodities due to their high moisture content, tender tissues and active metabolic processes after harvest. Even after detachment from the plant, vegetables remain physiologically active, continuing respiration and transpiration, which leads to rapid loss of freshness, weight, texture and nutritional quality if not properly managed (1). Post-harvest deterioration of vegetables poses a significant challenge in tropical and developing regions, where limitations in storage infrastructure, handling practices and transportation systems contribute to rapid quality loss and reduced economic returns (2). Therefore, the adoption of effective post-harvest technologies is essential to extend shelf life and maintain quality during storage and distribution.

Most above-ground vegetables possess a natural waxy cuticle on their outer surface that acts as a protective barrier against moisture loss, mechanical damage and microbial invasion (3). This natural wax layer plays a crucial role in regulating gas exchange and minimising transpiration. Vegetables such as tomato, cucumber, capsicum, brinjal, pumpkin, bottle gourd, ridge gourd and snake gourd naturally contain a thin cuticular wax layer that helps maintain firmness and freshness during storage. However, routine post-harvest operations such as washing, trimming, grading and packing often partially remove or disrupt this protective layer, making vegetables more susceptible to dehydration, shriveling, surface injury and decay (4). For instance, cucumber and tomato are highly prone to rapid moisture loss after washing, while capsicum and brinjal often show surface shriveling due to cuticle damage. Similarly, cucurbit vegetables such as pumpkin, bottle gourd and snake gourd may lose surface gloss and firmness when the natural wax coating is disturbed. As a result, the artificial restoration of this protective barrier has gained importance as a practical post-harvest intervention to maintain quality, reduce physiological weight loss and extend shelf life.

Wax coating, commonly referred to as waxing or skin surface coating, is defined as the artificial application of a thin, edible layer of wax, oil or wax-based formulation on the surface of vegetables as an addition to or replacement for the natural wax coating (5). Chemically, waxes are primarily composed of esters of long-chain fatty acids with monohydric alcohols, hydrocarbons and small amounts of free fatty acids, which impart hydrophobic properties and resistance to moisture movement (6). Commonly used food-grade waxes include carnauba wax, beeswax, paraffin wax and shellac, which are widely applied in post-harvest handling of fruits and vegetables. Carnauba wax, obtained from the leaves of *Copernicia prunifera* (Mill.) H.E.Moore, is valued for its high gloss and strong moisture barrier properties, while beeswax, a natural wax produced by honeybees, provides flexibility and good film-forming characteristics. Paraffin wax and shellac are also frequently used due to their effectiveness in reducing transpiration and improving surface appearance. These wax materials form a semi-permeable barrier that reduces water loss, delays respiration rate and helps maintain firmness, freshness and overall quality of vegetables during storage. When applied to vegetables, wax coatings form a semi-permeable membrane that modifies the internal atmosphere by restricting oxygen uptake and carbon dioxide release, thereby slowing respiration and metabolic activity (7).

One of the major advantages of wax coating in vegetable crops is its ability to reduce transpiration losses, which directly contributes to the maintenance of firmness, freshness and visual appeal during storage. Excessive moisture loss results in wilting, shriveling and loss of market value, particularly in vegetables such as cucumber, capsicum, brinjal and gourds (8). Wax coatings effectively seal microscopic cracks, lenticels and minor surface injuries caused during harvesting and handling, which otherwise serve as entry points for pathogens (9). By minimising water loss and surface damage, waxing significantly delays senescence and extends shelf life.

In addition to its physical barrier function, wax coating serves as a carrier system for incorporating functional additives such as fungicides, antimicrobials, growth regulators, antioxidants and sprout inhibitors. For example, imazalil and thiabendazole are commonly incorporated as fungicides to control post-harvest fungal diseases in vegetables and fruits, while chitosan, natamycin and essential oils (e.g. thyme oil and clove oil) are widely used as natural antimicrobial agents. Gibberellic acid (GA_3) and cytokinins are sometimes included as growth regulators to delay senescence and maintain freshness. Antioxidants such as ascorbic acid and citric acid help reduce oxidative deterioration and browning, whereas sprout inhibitors like chlorpropham (CIPC) are used particularly in the storage of tuber vegetables such as potato. The incorporation of these functional additives within wax coatings enhances their effectiveness by providing controlled release and prolonged protection, thereby improving shelf life, maintaining quality and reducing post-harvest losses. The incorporation of these compounds into wax formulations further enhances protection against microbial spoilage and physiological disorders, thereby improving storage performance of vegetables (10, 11). However, it is well recognised that wax coating cannot improve the inherent quality of inferior or damaged produce; rather, it is a complementary technology that is effective only when combined with good harvesting practices, proper sanitation and appropriate storage conditions (1).

The effectiveness of wax coating largely depends on the type of wax used, its formulation, method of application and uniformity of coverage. Natural waxes such as carnauba, beeswax and shellac, as well as mineral and synthetic waxes, are commonly used in vegetable coating, each differing in permeability, gloss, flexibility and compatibility with vegetable surfaces (12). Beeswax, a natural wax produced by honeybees, is widely used due to its good film-forming ability, moderate permeability and compatibility with many vegetable surfaces, making it suitable for maintaining firmness and reducing moisture loss during storage. Application methods including dipping, spraying, brushing and rolling have been developed, ranging from simple manual systems to mechanised waxing units designed for commercial operations. The construction and working principles of waxing equipment play a critical role in achieving uniform coating thickness, reducing material wastage and ensuring hygienic application under commercial packing conditions (3). With increasing emphasis on reducing post-harvest losses, improving shelf life and maintaining quality of fresh vegetables for domestic and export markets, wax coating technology has become an integral component of modern post-harvest management. Recent advances focus on edible, biodegradable and eco-friendly wax formulations that align with consumer preference for safe and sustainable food preservation practices (8). This review synthesises current knowledge on wax coating technology in vegetables, including types of waxes, application methods, mechanisms of action and their role in improving postharvest quality and shelf life. Recent advances in biodegradable and functional coatings are also discussed.

Mechanism of vegetable coatings

Post-harvest vegetable coatings function primarily by modifying the exchange of respiratory gases between the vegetable surface and the surrounding atmosphere. Upon application, the coating forms a semi-permeable barrier that restricts the diffusion of oxygen (O_2) into the tissue and carbon dioxide (CO_2) out of the tissue. This altered gaseous environment leads to partial depletion of O_2 and accumulation of CO_2 within the vegetable tissues, thereby creating conditions similar to controlled atmosphere storage (CAS) (1, 7). As a result, respiration rate decreases, metabolic activity slows and senescence is delayed, ultimately contributing to extended shelf life and improved post-harvest quality (Table 1).

Table 1. Vegetables suitable for wax coating and their post-harvest benefits

Category	Vegetable crop	Purpose/benefit of waxing	References
Mature fruit vegetables	Eggplant (brinjal)	Reduces moisture loss, delays shriveling and improves surface gloss and shelf life	(1, 8)
	Tomato	Slows respiration, delays ripening, reduces weight loss and surface cracking	(2, 5)
	Potato	Reduces moisture loss, delays sprouting when combined with inhibitors and improves appearance	(3, 4)
	Capsicum (bell pepper)	Minimises shriveling, maintains firmness and market quality during storage	(11, 12)
	Carrot	Reduces dehydration, surface whitening and weight loss	(2, 10)
	Pumpkin	Minimises physiological weight loss and rind dehydration and enhances storage life	(1, 3)
	Snake gourd	Maintains freshness, reduces moisture loss and improves shelf life under ambient storage	(4, 8)
Immature fruit vegetables	Cucumber	Controls transpiration loss, delays yellowing and shriveling and improves gloss	(7, 10)
	Summer squash	Reduces dehydration and surface softening and maintains visual quality	(2, 8)

In addition to gas regulation, vegetable coatings significantly influence water vapour diffusion, which is the primary cause of physiological loss in weight (PLW). The coating layer reduces the water vapour pressure gradient between the vegetable surface and surrounding air, thereby limiting transpiration and maintaining cell turgidity. According to the diffusion principle, $J = -D\,dC/dx$, the rate of moisture and gas movement depends on the diffusion coefficient and concentration gradient across the semi-permeable coating membrane. The application of wax coating reduces the effective diffusion coefficient, thereby slowing the movement of water vapour and respiratory gases.

The interaction between the coating material and the natural cuticular wax layer further enhances barrier efficiency. Edible coatings form a continuous film over microscopic cracks, pores and irregularities present on the vegetable surface, thereby strengthening the natural cuticle and improving resistance to moisture loss. This cuticle-coating interaction improves mechanical integrity and reduces permeability, particularly in vegetables with relatively thin or disrupted epicuticular wax layers after washing and handling.

Coatings also partially seal stomata, lenticels and micro-pores present on the vegetable epidermis, thereby reducing uncontrolled diffusion of gases and water vapour. Partial sealing of these openings moderates respiration without completely blocking gas exchange, ensuring that anaerobic conditions are avoided when optimal coating thickness is maintained. The combined effects of reduced transpiration, moderated respiration and improved surface protection contribute to maintenance of firmness, delayed shriveling and preservation of overall quality during storage and transportation. Thus, vegetable coatings function through a combination of physical barrier formation, diffusion regulation and structural reinforcement of the natural cuticle, resulting in reduced moisture loss, slower metabolic activity and extended storage life of fresh vegetables.

However, the effectiveness of vegetable coating depends greatly on the type of coating material and its concentration. If surface coatings are not properly selected or applied at excessive thickness, the restriction of gas exchange may become too severe. This excessive impairment of respiration can result in anaerobic metabolism, leading to the production of ethanol and acetaldehyde, which are responsible for off-odours and off-flavours (5, 9). Over-waxing has also been reported to cause abnormal ripening patterns, uneven colour development and excessive softening, thereby reducing consumer acceptance and marketability (4).

Vegetable coatings can be formulated using a wide range of materials, including lipids, natural resins, polysaccharides, proteins and synthetic polymers. Lipid-based coatings are particularly effective in reducing moisture loss due to their hydrophobic nature, whereas polysaccharide- and protein-based coatings provide better gas permeability but limited water vapour resistance (6, 13). In practice, most commercial coatings are composite systems combining two or more film-forming materials to balance gas exchange and moisture control.

To improve flexibility and prevent brittleness, low molecular weight compounds such as polyols (e.g., glycerol and sorbitol) are commonly added as plasticisers. These plasticisers increase the elasticity and fluidity of the coating, reducing the risk of cracking or flaking during handling and storage (10). Surfactants, emulsifiers and antifoaming agents are incorporated to improve dispersion, enhance adhesion and ensure uniform coating during application (8). Wax fruit coating acts as a multifunctional post-harvest treatment by regulating respiration, reducing moisture loss and protecting against physiological and microbial deterioration. However, careful selection of coating materials, formulation and application rate is essential to achieve desirable quality retention without inducing adverse effects.

Types of wax coating in vegetables

Natural waxing

Natural waxing refers to the waxy layer that is inherently present on the surface of many vegetable crops at the time they attain physiological or marketable maturity, commonly known as bloom, which appears as a thin whitish or glaucous layer and serves as the plant's first line of defense against moisture loss, mechanical injury and microbial invasion (1). This natural wax layer plays a vital role in regulating transpiration and gas exchange by acting as a semi-permeable barrier on the vegetable surface, thereby reducing excessive water loss and protecting produce from environmental stress and microbial contamination during post-harvest handling and storage (3). However, the natural wax coating is easily disrupted or removed during post-harvest operations such as harvesting, washing, grading, packaging and transportation. Repeated handling significantly reduces the effectiveness of this protective layer, thereby increasing susceptibility to dehydration and quality deterioration (2). Vegetables such as cucumber, carrot and potato commonly exhibit a visible natural bloom, which diminishes rapidly after harvest if no protective measures are adopted (4).

Artificial waxing

Artificial waxing is a post-harvest treatment in which vegetables are coated with a thin layer of wax or wax-based emulsion to supplement or replace the natural wax layer. In this process, produce is typically dipped, sprayed or brushed with a wax emulsion and allowed to dry for a short period, resulting in the formation of a uniform wax layer generally less than 1 µm in thickness on the surface (7). This artificial wax coating effectively seals microscopic pores, cracks and surface injuries, thereby reducing transpiration and respiration rates and extending shelf life (5). In addition to its physiological benefits, artificial waxing improves the external appearance of vegetables by imparting shine and luster, thereby enhancing visual appeal, consumer preference and overall market value, which contributes to better price realisation and reduced post-harvest economic losses (8). Depending on formulation and application method, artificial wax coatings can be classified into solvent-based waxes, water-based wax emulsions and paste or oil-based waxes. These waxes differ in their permeability characteristics, gloss and compatibility with different vegetable surfaces (12). Artificial waxing is widely adopted as a commercial post-harvest practice, provided it is applied at appropriate concentrations to avoid adverse effects such as anaerobic respiration and off-flavour development (4).

Types of food-grade waxes

Food-grade waxes are widely employed in the post-harvest handling of vegetables to form a thin, edible protective coating that minimises moisture loss, moderates respiration rate and enhances surface appearance. These coatings play a critical role in extending shelf life and maintaining market quality during storage and transportation. A variety of raw materials are used as base components for food-grade wax formulations, each differing in physical and functional properties. Among these, paraffin wax, carnauba wax, shellac and polyethylene-based waxes remain the most extensively utilised in commercial waxing operations due to their proven effectiveness and regulatory acceptance (8, 14, 15). Differences in gloss, hardness, gas permeability and compatibility with specific vegetable surfaces determine the suitability of each wax type for particular commodities and storage conditions. The major types of food-grade waxes used for post-harvest coating of vegetable crops are presented in Fig. 1. Commercial formulations derived from these wax materials are marketed under various trade names and are widely adopted in vegetable packing industries, as summarised in Table 2.

Paraffin wax, a petroleum-derived product, provides an excellent barrier against moisture loss but exhibits relatively low permeability to respiratory gases. Consequently, it is primarily used for vegetables in which moisture loss control is critical, such as underground or root vegetables, because its low gas permeability may otherwise induce anaerobic conditions in highly respiring produce (15, 16). Carnauba wax, obtained from the leaves of *C. prunifera*, is a natural plant-based wax characterised by a high melting point, hardness and superior gloss and moderate gas permeability, making it suitable for a wide range of fresh vegetables, exhibits moderate gas permeability compared to shellac and paraffin (14, 17). Shellac, a resinous secretion produced by the lac insect, is valued for its excellent film-forming ability, strong adhesion and high surface shine, although excessive application may restrict gas exchange and induce anaerobic conditions (8, 18). Polyethylene-based waxes are synthetic polymers that produce flexible, uniform coatings with balanced moisture and gas permeability and are commonly incorporated into modern commercial wax formulations because of their consistency and durability, offering more uniform performance than natural waxes under industrial conditions (19).

Less commonly used wax bases include beeswax and candelilla wax, both of which are natural materials with good film-forming properties and moderate permeability characteristics. Beeswax provides flexibility and a natural appearance, while candelilla wax offers greater hardness and resistance to moisture loss; however, their higher cost and limited availability restrict their large-scale commercial use (8, 20). These waxes provide moderate gas permeability but lower commercial scalability. Each wax base possesses unique characteristics influencing coating firmness, surface gloss, gas diffusion and durability, necessitating careful selection based on vegetable type and intended storage duration.

In commercial practice, raw wax materials are emulsified in water using appropriate emulsifiers, stabilisers and wetting agents to produce a uniform, continuous coating suitable for application by brushing, spraying or roller systems. Most food-grade waxes available today are supplied as ready-to-use formulations, ensuring consistency in coating performance and ease of application on commercial packing lines (14, 15). The

Table 2. Trade names of extensively used commercial waxes for vegetable crops

Sl. No.	Trade name	Manufacturer/source	Type/composition	Key features and applications in vegetables	References
1	Citrashine®	DECCO (UPL Ltd.), India	Food-grade wax emulsion (shellac and resin based)	Provides high gloss, reduces moisture loss, commonly used on tomato, capsicum, cucumber and brinjal; suitable for spray and roller application	(1, 21)
2	Waxol-12	Commercial post-harvest suppliers	Oil-in-water emulsion wax containing ~12 % solids	Forms thin uniform coating; reduces transpiration and shriveling; used on tomato, cucumber, carrot and potato	(2, 22)
3	Tal-Prolong	T. Stanes & Co. Ltd., India	Proprietary wax emulsion (plant-based and resin components)	Extends shelf life by lowering respiration and water loss; improves surface sheen of vegetables such as tomato, capsicum, cucumber and pumpkin	(23, 24)
4	Semper Fresh®	Pace International LLC	Polysaccharide-based edible coating	Semi-permeable coating that modifies internal atmosphere; delays senescence and reduces weight loss in tomato, cucumber, capsicum and eggplant	(25, 26)
5	Frutox	Commercial wax formulation	Emulsion of mixed waxes with ~12 % solids	Provides moderate gloss and protection against dehydration; suitable for spray, dip and roller brushing on tomato, capsicum, cucumber and snake gourd	(2, 22)



Carnauba wax



Beeswax

Paraffin wax



Paraffin wax



Polyethylene-based waxes



Shellac wax

Fig. 1. Major types of food-grade waxes used for post-harvest coating of vegetable crops.

quantity of wax applied per individual vegetable is minimal; for example, one gallon of liquid carnauba-, shellac-, or polyethylene-based wax can coat tens of thousands of vegetables, demonstrating high application efficiency (16). In contrast, paraffin wax is generally applied as a thicker coating, particularly for root and underground vegetables, resulting in fewer units being coated per gallon because of the higher wax requirement (15). Thus, appropriate selection of wax type, formulation and application method is essential for optimising post-harvest quality, shelf life and marketability of vegetables. Natural waxes generally provide better biocompatibility and consumer acceptance, whereas synthetic waxes offer greater consistency and scalability. Recent developments include nano-emulsified wax coatings and biodegradable composite formulations aimed at improving barrier properties and environmental sustainability.

Commercial waxes used for vegetable coating

- Shellac
- Carnauba wax
- Beeswax
- Polyethylene wax
- Wood resins
- Paraffin wax

Shellac wax

Shellac is a natural resin obtained from the secretions of the lac insect *Kerria lacca* (formerly *Laccifer lacca*), which deposits resinous material on the twigs and branches of host trees. The raw lac is collected and processed through crushing, washing, filtration and refining to obtain food-grade shellac suitable for use as an edible coating on fruits and vegetables (27, 28). Due to its natural

origin and film-forming ability, shellac has long been used in post-harvest handling to enhance produce appearance and storage life. At normal ambient temperatures, shellac remains hard and brittle, but it softens upon heating and becomes pliable, allowing it to form a smooth and continuous coating over the produce surface. Shellac coatings are characterised by high hardness, strong adhesion and excellent resistance to moisture loss, producing a bright and glossy finish that improves the visual appeal and marketability of fresh fruits and vegetables (12, 29). These properties make shellac particularly effective in reducing post-harvest weight loss under ambient storage conditions.

However, shellac exhibits relatively low permeability to respiratory gases such as oxygen and carbon dioxide compared to other natural waxes like carnauba. Excessive coating thickness or improper application may restrict gas exchange, leading to anaerobic respiration, accumulation of fermentation products and development of off-flavours in coated produce (1, 3). In addition, shellac-coated fruits stored at low temperatures may develop surface whitening or chalking upon transfer to ambient conditions, which can adversely affect consumer acceptance (2, 30). Therefore, careful control of shellac concentration and coating thickness is essential to balance moisture retention, respiration regulation and overall fruit quality during storage and marketing.

Carnauba wax

Carnauba wax is a natural plant-derived wax obtained from the leaves of the carnauba palm (*C. prunifera*), native to northeastern Brazil. The wax is secreted on the leaf surface as a natural protective mechanism against desiccation and high temperatures. Commercially, the wax is recovered by drying the leaves followed by mechanical removal and purification, yielding appreciable quantities of wax suitable for food-grade applications (31, 32). Due to its renewable origin and safety for consumption, carnauba wax is extensively incorporated into edible coating formulations used in the post-harvest handling of vegetables. Carnauba wax produces a uniform, moderately glossy surface on coated produce and provides greater shine than mineral waxes such as paraffin, although the gloss level is generally lower than that achieved with resin-based coatings. The wax forms a hard yet durable film that effectively reduces moisture loss while maintaining sufficient flexibility when appropriately emulsified with plasticisers and surfactants (33, 34). These characteristics contribute to improved surface appearance and reduced post-harvest weight loss during storage.

A key advantage of carnauba wax is its relatively higher permeability to respiratory gases compared to shellac-based coatings. This balanced permeability enables normal gas exchange, thereby minimising the risk of anaerobic respiration, internal fermentation and the development of off-flavours in coated vegetables (3, 30). Furthermore, carnauba wax coatings remain stable under refrigerated storage and do not exhibit whitening or chalking upon transfer to ambient conditions, thereby enhancing visual quality and consumer acceptability (32, 34). Owing to its favourable combination of moderate gloss, moisture barrier efficiency, gas permeability and stability under low-temperature storage, carnauba wax is widely preferred for vegetables requiring an extended shelf life. However, due to its relatively higher cost, it is often blended with other waxes or polymers to improve coating performance while maintaining economic feasibility in commercial operations (31, 33).

Polyethylene-based waxes

Polyethylene-based waxes are synthetic wax materials produced through the controlled polymerisation of ethylene, resulting in low-molecular-weight polymers with wax-like properties. These waxes are widely used in post-harvest coating formulations for fruits and vegetables due to their relatively low cost, ease of emulsification and compatibility with commercial packinghouse operations (35, 36). Their synthetic origin allows consistent quality and performance across batches, making them suitable for large-scale post-harvest applications. Polyethylene waxes form flexible and uniform surface coatings that provide moderate gloss and effective protection against moisture loss and surface abrasion during handling, storage and transportation. When applied as aqueous emulsions, these waxes adhere well to vegetable surfaces and help maintain firmness and external appearance without excessively restricting physiological processes (37, 38). Their mechanical flexibility also reduces the risk of cracking or flaking under fluctuating storage temperatures.

Compared to natural waxes such as shellac and carnauba, polyethylene-based waxes exhibit relatively higher permeability to respiratory gases, allowing sufficient oxygen uptake and carbon dioxide release. This balanced gas exchange minimises the risk of anaerobic respiration, fermentation and the development of off-flavours in coated produce (30, 39). Owing to these properties, polyethylene waxes are commonly used on a wide range of fresh produce, including tomatoes, bell peppers, cucumbers, eggplants, citrus fruits, apples and mangoes, where both visual quality and physiological stability are required. In commercial practice, polyethylene wax formulations are frequently blended with suitable emulsifiers, plasticisers and stabilising agents to enhance coating uniformity, adhesion and surface sheen. These formulations are typically supplied as ready-to-use emulsions, enabling easy integration into existing post-harvest handling and packing line systems (35, 36). Due to their versatility, cost effectiveness and balanced functional properties, polyethylene-based waxes continue to play an important role in modern post-harvest management of vegetables.

Wood resins

Wood resins are natural exudates primarily obtained from coniferous tree species such as pine (*Pinus* spp.) and spruce (*Picea* spp.). These resins are complex mixtures of resin acids, diterpenes and neutral compounds that provide strong film-forming and protective properties. After purification and refinement, wood resins are used as functional components in edible coatings and wax formulations for post-harvest applications in vegetables (40, 41). Their natural origin and strong hydrophobic nature make them effective in reducing surface moisture loss. When applied as thin coatings, wood resin-based formulations form semi-permeable barriers on vegetable surfaces, thereby lowering transpiration rates while moderately regulating respiration during storage and marketing. Such coatings are particularly beneficial for vegetables with tender or semi-permeable skins, where excessive dehydration can rapidly reduce market quality (3, 39). Due to their relatively rigid film structure, wood resins are commonly blended with other waxes or polymers to improve coating flexibility and surface smoothness.

Wood resin formulations are frequently combined with plant-based waxes to enhance coating uniformity, durability and surface gloss while avoiding excessive restriction of gaseous

exchange. These blended coatings improve firmness retention and delay shriveling without inducing anaerobic conditions (33, 37). Their stability under ambient and refrigerated storage conditions further supports their use in commercial post-harvest handling systems. In vegetable crops, wood resin-containing coatings have been reported to be suitable for cucumber, capsicum, eggplant (brinjal), tomato, carrot and pumpkin, where they contribute to improved firmness, reduced weight loss and enhanced surface sheen during short- to medium-term storage (30, 36). In underground vegetables such as potato and carrot, resin-based coatings effectively limit surface dehydration and delay senescence by reducing transpiration losses (28). Although wood resins are of natural origin, only purified and food-grade resin derivatives are recommended for post-harvest use, as crude resins may cause uneven coating or sensory defects if improperly formulated (41).

Paraffin wax

Paraffin wax is a petroleum-derived wax obtained during the fractional distillation and refining of crude oil. It consists mainly of saturated hydrocarbons and has long been used as a protective coating material in food preservation and post-harvest handling due to its hydrophobic nature and low-cost availability (42, 43). At ambient temperature, paraffin wax remains solid and must be heated to approximately 50–55 °C to achieve a molten state suitable for coating application. The temperature of the molten wax significantly influences coating clarity, adhesion and uniformity, with controlled heating producing smoother and more translucent coatings after solidification (28). One of the notable properties of paraffin wax is its thermal stability, which allows it to undergo repeated cycles of melting and solidification without substantial degradation of its physical characteristics. This property makes paraffin wax suitable for repeated use in post-harvest operations, particularly in traditional waxing practices for vegetables (44). When applied as a thick coating, paraffin wax forms a highly effective moisture barrier that markedly reduces transpiration and surface dehydration during storage.

Due to its very low permeability to respiratory gases, paraffin wax significantly restricts oxygen and carbon dioxide exchange. While this characteristic may be undesirable for actively respiring fruits, it is advantageous for root and tuber vegetables, where moisture conservation is of greater importance than gas exchange (30, 39). Consequently, paraffin wax is commonly used for underground and ground-contact vegetables such as potato, carrot, beetroot, yam and cassava, where it effectively reduces weight loss, surface shriveling and mechanical damage during long-term storage and transportation (42, 43).

Paraffin wax is commonly used in export marketing of cassava, where it significantly extends shelf life by minimising physiological deterioration and microbial infection (45). In addition to cassava, paraffin waxing has been successfully applied to sweet potatoes and yams to reduce post-harvest weight loss and enhance marketability during storage and shipping (46, 47). However, due to its low permeability to respiratory gases, paraffin wax is generally restricted to underground storage organs rather than climacteric fruits.

Methods of wax application in vegetable crops

Wax coatings are applied using different techniques depending on scale of operation, type of vegetable and desired coating uniformity.

Spray waxing

Spray waxing is the most widely adopted commercial method for waxing vegetables due to its efficiency, uniformity and compatibility with automated packing lines. In this method, vegetables conveyed on roller conveyors are uniformly sprayed with a water-based wax emulsion using calibrated nozzles. After application, the produce is passed through a warm air-drying tunnel maintained at approximately 50–55 °C, which promotes rapid evaporation of moisture and proper setting of the wax film on the surface (48, 49). Spray waxing allows precise control over wax dosage and is commonly used for vegetables such as tomato, capsicum, cucumber, brinjal, pumpkin and snake gourd in commercial handling systems.

Two spray systems are generally employed: low-pressure spraying and high-pressure atomisation. Low-pressure spraying produces relatively larger droplets and is suitable for vegetables with firm skins, while high-pressure atomising systems generate fine droplets that enhance surface coverage, improve coating uniformity and reduce wax consumption (50, 51). Proper optimisation of spray pressure, nozzle type and drying conditions is essential to avoid uneven coating, wax streaking or excessive restriction of gas exchange, which could otherwise lead to physiological disorders during storage (25, 52).

Dipping

In the dipping method, vegetables are immersed in a prepared water-based wax emulsion for about 30–60 sec to ensure uniform contact of the coating solution with the entire surface. The produce is usually placed in perforated plastic crates or wire baskets holding approximately 25–30 kg and submerged in tanks containing the wax formulation (53). This technique is simple to operate and is particularly suitable for vegetables with uneven surfaces where achieving a uniform coating through spraying may be difficult.

After dipping, the vegetables are removed and dried either under forced air using electric fans or by passing warm air at 50–55 °C to accelerate water evaporation and ensure proper wax film formation. During drying, the produce is occasionally turned to prevent uneven deposition and wax accumulation on one side (54). The dipping method is widely adopted in small-scale and semi-commercial post-harvest handling systems for vegetables such as cucumber, carrot, potato, tomato and capsicum, where gentle handling and low operational cost are essential (55). Properly applied dipping treatments have been shown to reduce physiological weight loss, delay senescence and improve visual quality during short-term storage and marketing (56).

Foam application

Foam application is regarded as an efficient and precise method of wax application, as it produces a very thin, uniform coating on vegetable surfaces after the evaporation of water. In this technique, a foam generator is positioned above rotating brushes or applicator heads and the wax emulsion is delivered in the form of stable foam as vegetables move along the packing line. The foam structure allows controlled deposition of wax with minimal dripping, thereby ensuring uniform surface coverage (57). One of the major advantages of foam waxing is the significant reduction in wax runoff and over-application compared to conventional spray systems. The controlled release of wax minimises wastage and improves coating efficiency, while excess foam can be collected

and recycled through catch pans installed beneath the applicator unit (58). This method is especially beneficial for vegetables that require light and breathable coatings to maintain normal respiration.

Foam application has been found particularly suitable for vegetables such as tomato, capsicum, cucumber and snake gourd, where it helps in reducing moisture loss, maintaining firmness and improve surface appearance without causing excessive restriction of gaseous exchange (59). Due to its efficiency, economy and gentle handling of produce, foam waxing is increasingly preferred in modern packinghouse operations for fresh market vegetables.

Flooding in wax coating of vegetables

Flooding is a post-harvest wax application technique similar to dipping, offering a simple, safe and efficient means of coating vegetables. In this method, a continuous stream of wax emulsion flows over the surface of vegetables as they move along a conveyor system. Excess wax drains naturally, leaving a uniform and controlled coating that improves moisture retention and reduces surface dehydration (60, 61).

This method is particularly suitable for vegetables with smooth or firm surfaces, such as cucumber, tomato, pumpkin and snake gourd and is easily integrated into automated packing lines for high-throughput operations. Flooding ensures minimal mechanical handling, reducing the risk of surface bruising or damage while providing consistent coverage across all produce units (62). Properly optimised flooding systems can improve shelf life, maintain visual quality and reduce post-harvest losses during storage and transportation.

Roller brushing

Roller brushing is a highly efficient method for the uniform application of liquid waxes on vegetables in commercial packing operations. In this system, wax emulsion is dispensed from above onto a series of rotating roller brushes. As vegetables pass through the rollers, the brushes become saturated and simultaneously rotate, spinning the produce, ensuring even distribution of wax across all surfaces (63).

Typically, multiple roller brushes are arranged in sequence within a waxing unit and full saturation of the brushes before operation is essential to achieve uniform coating. Roller brushing provides precise control over the thickness of the wax layer, minimising over-application and preventing uneven coatings that could impair respiration or appearance (64). This method is widely adopted for vegetables such as tomato, capsicum, cucumber, pumpkin and snake gourd due to its efficiency, adaptability to high -throughput packing lines and ability to maintain surface quality during post-harvest handling (65). Properly optimised roller brushing systems also help reduce post-harvest weight loss, maintain gloss and extend shelf life of fresh-market vegetables.

Each application method differs in coating uniformity, wax consumption, operational cost and suitability for specific vegetables. Spray and roller brushing are preferred for large-scale commercial operations due to precision and efficiency, whereas dipping and flooding are more suitable for small-scale or irregular-shaped produce. Foam application offers improved coating uniformity with minimal wastage.

Use of wax concentration on fresh vegetable crops

The concentration of wax applied to fresh vegetables is a critical factor determining the effectiveness of post-harvest treatments in maintaining quality and extending shelf life. Optimal wax concentrations ensure the formation of a thin, uniform and semi-permeable coating on the vegetable surface, which reduces water loss and moderates respiration without inducing anaerobic conditions (59, 61). Both insufficient and excessive wax application can adversely affect storage quality, making careful optimisation essential. Low wax concentrations often result in incomplete coverage, leaving portions of the surface exposed and vulnerable to transpiration, surface shriveling and physiological deterioration. Conversely, excessively high wax concentrations may severely restrict gaseous exchange, leading to the accumulation of carbon dioxide, oxygen depletion and anaerobic conditions in the tissue. These effects can cause off-odours, off-flavours, uneven ripening, surface discoloration and accelerated softening of vegetables (57, 58). Therefore, the optimal wax concentration must be adjusted according to vegetable type, skin permeability and intended storage conditions.

Commercial wax formulations are generally applied at concentrations ranging from 5 % to 15 % total solids, depending on the wax type and method of application. Wax emulsions containing approximately 10–12 % solids have been found effective for vegetables such as tomato, capsicum, cucumber, brinjal, carrot and pumpkin, providing a glossy finish and adequate protection while maintaining normal respiratory activity (63). The recommended wax concentration ranges for different vegetables and their effects on post-harvest quality are summarised in Table 3. Polysaccharide-based coatings, such as alginate- or chitosan-based edible films, are typically applied at lower concentrations to avoid excessive restriction of gas exchange and ensure proper post-harvest metabolism (54, 56).

The method of application also influences the effective concentration of wax on the produce surface. Techniques such as roller brushing and foam application generally require lower wax concentrations due to better distribution and reduced wastage, whereas dipping and flooding methods require careful monitoring to prevent over-deposition (64, 65). Uniformity of coating is as important as concentration, as uneven layers can compromise shelf life and surface quality. Overall, applying wax at the appropriate concentration is essential to maximise benefits, including extended shelf life, improved appearance, reduced post-harvest losses and maintenance of quality and safety in fresh vegetables.

Advantages of wax coating on vegetables

Application of food-grade wax coatings on fruits and vegetables significantly improves their external appearance by enhancing surface gloss and visual appeal, thereby increasing consumer preference and market acceptability. Wax coatings reduce PLW by limiting transpiration and surface dehydration, which helps minimise moisture loss and delays wilting and shriveling during storage. The semi-permeable film formed on the commodity surface modifies the internal atmosphere by reducing oxygen availability and slowing respiration rate, which in turn delays senescence and prolongs storage life.

Waxing also reduces the incidence of certain physiological disorders such as chilling injury and enzymatic browning in susceptible vegetables. In addition, the wax layer acts as a protective barrier against minor mechanical injuries such as bruising during handling, packaging and transportation. The

Table 3. Recommended wax concentrations and their effects on fresh vegetable crops

Sl. No.	Vegetable	Type of wax/coating	Recommended wax concentration (solids %)	Method of application	Effect on quality and shelf life	References
1	Tomato	Carnauba wax/nano-emulsion	9–12 %	Spray/roller brushing	Reduces weight loss, maintains firmness, improves gloss and extends storage life	(66)
2	Capsicum	Carnauba/composite wax blend	8–10 %	Spray/foam	Maintains firmness, reduces shriveling and slows respiration	(67)
3	Cucumber	Mixed wax emulsion	6–10 %	Spray/dipping	Reduces moisture loss and surface shriveling and extends freshness	(65)
4	Brinjal (eggplant)	Carnauba-based edible coating	8–12 %	Spray/roller brushing	Enhances appearance, retains firmness and delays senescence	(68, 69)
5	Carrot	Mixed lipid-based coating	5–8 %	Dipping/flooding	Minimises dehydration and weight loss	(70, 71)
6	Potato	Paraffin/composite coating	6–8 %	Dipping	Reduces moisture loss and limits shriveling during storage	(72, 73)
7	Pumpkin	Biopolymer-wax blend	8–10 %	Spray/roller brushing	Maintains surface sheen and reduces water loss	(74, 75)
8	Snake gourd	Biopolymer-wax emulsion	8–10 %	Spray/foam	Delays shriveling and enhances marketability	(76)

coating further restricts entry of pathogens through surface openings, thereby reducing microbial infection and spoilage. Wax coatings can serve as carrier agents for functional additives, including sprout inhibitors, growth regulators and preservatives, thus improving post-harvest management efficiency. Moreover, waxing is considered a cost-effective alternative or supplement to refrigerated storage, especially in situations where cold storage facilities are limited, as it contributes to reduction of spoilage and extension of shelf life.

Disadvantages of wax coating on vegetables

Despite several advantages, improper application of wax coatings may lead to development of off-flavours in fruits and vegetables. This undesirable flavour change is mainly due to excessive restriction of oxygen and carbon dioxide exchange, which induces anaerobic respiration and results in accumulation of ethanol and acetaldehyde in the tissues. Such physiological imbalance may negatively affect product quality and consumer acceptance.

Conclusion

Wax coating technology plays a significant role in post-harvest management of vegetables by reducing physiological loss in weight (PLW), slowing respiration, minimising moisture loss and enhancing visual appeal. The use of appropriate food-grade waxes, applied at optimal concentrations and through suitable methods, results in extended shelf life and improved marketability without compromising quality or safety. Different wax materials and application techniques must be carefully selected based on the vegetable type, surface characteristics and storage conditions to avoid problems such as off-flavour development and abnormal physiological changes.

Waxing is particularly valuable as a low-cost alternative or supplement to refrigerated storage, especially in developing regions with limited cold-chain infrastructure. Additionally, wax coatings offer the advantage of serving as carriers for sprout inhibitors, growth regulators and preservatives, further improving post-harvest quality management. Future research should focus on developing environmentally friendly and biodegradable wax formulations, refining application technologies and optimising wax-vegetable interactions to maximise benefits while ensuring consumer safety. Overall, wax coating remains a promising and sustainable post-harvest technology for reducing vegetable losses and improving supply chain efficiency. The effectiveness of wax coatings depends on achieving a balance between moisture barrier properties and adequate gas permeability. Emerging approaches such as biodegradable coatings, nano-emulsions and functionalised wax systems offer new opportunities for improving performance and sustainability. These technologies have implications for reducing postharvest losses and enhancing food security, particularly in developing regions.

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Authors' contributions

JM, KY, KRV, VJ, RR, AS, SK and TUM carried out the conceptualisation. JM, KC, VVR, AM, SN and NM performed the formal analysis. AS, SK, TUM, KD and VJ conducted the supervision and validation. JM, KRV and VJ carried out the language editing. All authors have read and approved the final manuscript.

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