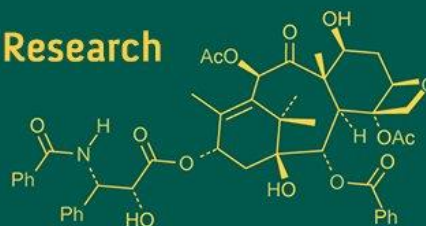
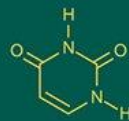
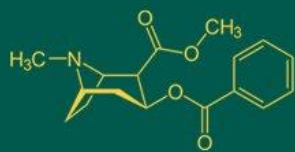


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Sustaining freshness innovative postharvest management for vegetables

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Abstract

Postharvest management of vegetables is essential for maintaining quality, extending shelf life, and minimizing losses throughout the supply chain. Among various factors, temperature control plays a pivotal role in regulating physiological processes such as respiration, transpiration, and microbial activity. Proper storage temperatures help reduce weight loss, preserve nutritional quality, and delay senescence, although exposure to excessively low temperatures may cause chilling injury in sensitive crops like leafy vegetables. Research findings indicate that optimized storage conditions, including appropriate packaging and low-temperature storage, significantly enhance moisture retention and reduce deterioration. Moreover, innovative treatments such as melatonin application have shown potential in improving antioxidant activity and extending storage life.

Recent advancements in postharvest technology highlight the growing importance of sustainable and smart solutions. Emerging approaches such as nanotechnology-based edible coatings, advanced Modified Atmosphere Packaging (MAP), plasma technology, High-Pressure Processing (HPP), and Pulse Electric Fields (PEF) offer promising opportunities to enhance shelf life while maintaining product quality. In addition, digital innovations like blockchain technology and predictive analytics are improving traceability and supply chain efficiency. However, the adoption of these technologies faces several challenges, including high implementation costs, lack of infrastructure, limited technical knowledge, and regulatory constraints. Consumer concerns regarding safety and acceptance of advanced technologies further add to these challenges.

In conclusion, integrating innovative postharvest technologies with efficient storage practices can significantly reduce losses, maintain quality, and contribute to food security. Addressing technological and economic barriers will be crucial for the successful implementation of these advancements in the future.

Keywords: Postharvest management, temperature control, shelf life, chilling injury, Modified Atmosphere Packaging (MAP), supply chain, food security

Introduction

Vegetables occupy a prominent position in the global agricultural economy and play a vital role not only as a source of food but also in promoting economic development and human health. Postharvest losses of horticultural crops refer to the quantitative and qualitative deterioration that occurs from harvest until consumption. India is the second-largest producer of vegetables in the world after China, with an annual production of 204.61 million tonnes from an area of 11.35 million hectares. However, postharvest losses in vegetables are among the highest across all food commodities, ranging from 5 to 12% of total production (APEDA, 2023).

A diverse and balanced diet rich in vegetables is essential for obtaining a wide range of vitamins, minerals, and phytochemicals that support overall health. The Indian Council of Medical Research (ICMR, 2024) recommends a daily intake of 400 g of vegetables per adult. Despite their importance, countries with agriculture-based economies face significant challenges related to postharvest losses due to the highly perishable nature of vegetables (Kirci *et al.*, 2022) ^[25].

The short shelf life of vegetables contributes to nearly 70% of total food waste, primarily due to inadequate transportation and storage infrastructure. Vegetables may lose 20-30% of their value after harvest due to losses occurring at different stages, including harvesting (38%), processing and packaging (19%), distribution (19%), postharvest handling and storage (15%), and consumption (9%) (Sharma *et al.*, 2024) ^[48].

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Postharvest losses of fruits and vegetables have serious implications for farmers' income and food security. These losses are mainly attributed to inadequate preservation techniques, inefficient transportation systems, and poor marketing infrastructure (De *et al.*, 2024) ^[13]. Effective postharvest management involves a series of operations such as cooling, cleaning, sorting, grading, packaging, storage, and transportation (Chhetri *et al.*, 2023) ^[10]. Reported that the highest postharvest losses occur in tomato, while the lowest are observed in radish. Therefore, improving postharvest practices and developing efficient technologies are essential for maintaining quality, extending shelf life, and ensuring food security (Workineh and Lemma, 2020) ^[63].

Maintaining freshness in vegetables is a critical aspect of postharvest management, as it helps preserve quality, nutritional value, and shelf life. Several key factors influence the freshness and quality of vegetables, which are discussed below.

Harvesting maturity

Harvesting refers to the process of collecting crops from the field at the appropriate stage of maturity. In vegetables, harvesting is generally carried out at the stage considered suitable for consumption. Fruits are typically harvested at physiological maturity, when they attain maximum dry weight, whereas vegetables are harvested at horticultural or field maturity (Pokhrel, 2021) ^[37].

Proper handling during harvesting is essential to minimize mechanical damage such as bruising, cuts, and punctures. Harvesting during cooler hours of the day and providing shade immediately after harvest are recommended practices to reduce field heat and prevent wilting (Ridolfi *et al.*, 2018) ^[43]. Harvesting should also be avoided during rainy conditions, as excess moisture promotes microbial growth.

Harvesting at the correct maturity stage is crucial for maintaining quality, shelf life, and marketability. For instance, tomatoes intended for long-distance transport are harvested at the breaker stage, whereas leafy vegetables such as lettuce are harvested when fully developed but before bolting.

In bitter melon, maturity is difficult to assess visually; however, external fruit color and seed coat color can serve as indicators. Aminah and Anna (2011) ^[65] reported that ripening in bitter melon increases physicochemical properties and total phenolic content, while reducing antioxidant activity (DPPH scavenging activity). Typically, bitter melon is harvested 12-20 days after flowering, depending on the variety, before full seed development (Dhillon *et al.*, 2017) ^[66]. Baburao (2013) ^[3] suggested that bitter melon (variety Preethi) can be harvested at 14-15 days after flower opening without economic loss.

Tolasa *et al.* (2021) ^[59] demonstrated that harvesting stage and

Pre-storage treatments significantly influence tomato shelf life. Tomatoes harvested at the light red stage and treated with water showed maximum decay, whereas those harvested at the mature green stage and treated with 50% cactus mucilage exhibited minimum decay and weight loss. The highest weight loss (62.47%) was recorded in mature green tomatoes treated with water after 20 days of storage, while the lowest weight loss (12.77%) was observed in light red tomatoes treated with cactus mucilage.

The maturity stage at harvest significantly affects postharvest quality attributes such as taste, firmness, and shelf life (Beckles, 2012) ^[5]. Tomatoes, being climacteric fruits, can be harvested at different stages, including mature green, breaker, turning, pink (light red), and red. These stages influence parameters such as soluble solids, acidity, pH, color, firmness, nutrient content, and storage life (Teka, 2013) ^[66]. According to Ramady *et al.* (2015) ^[42] as shown in table 1, the maturity duration of some common vegetables is as follows:

Crop	Early Variety (days)	Late Variety (days)
Tomato	65	100
Beetroot	50	80
Cabbage	62	110
Cauliflower	55	65
Okra	50	60
Mustard	40	60
Onion	85	120
Pea	58	77
Potato	90	120
Beans	46	65
Pumpkin	110	120

Grading

Grading is an essential postharvest operation that involves sorting vegetables based on quality attributes such as size, shape, color, maturity, and absence of defects. It ensures uniformity, enhances market value, and improves consumer acceptance. Vegetables are graded based on the following criteria:

- **Size and Shape:** Uniformity is important for packaging and market appeal.
- **Color:** Indicates maturity and quality, influencing consumer preference.
- **Maturity:** Determines taste, texture, and storage potential.
- **Defects:** Includes bruises, cuts, pest damage, and blemishes.
- **Weight:** Used as a grading parameter in certain crops.
- **Firmness:** Reflects freshness and quality.
- **Internal Quality:** Includes texture, flavor, and seed development.

Species and characteristics	Grading Standard and country	Grading classification	References
Tomato (color and defects)	Color image and machine learning	Three categories Health (97.67%), Defected (92.63%), and average (95.15%)	Ireri <i>et al.</i> , 2019 ^[20]
Chili (color - lightness, chroma, hue)	Tristimulus colorimetry	D65 standard illuminant and two degree observer rt6standard	Sajjan <i>et al.</i> , 2020 ^[46]
Cow pea	ASEAN standards	Extra class, class 1, class 2	ASEAN, 2013

Globally, grading plays a crucial role in addressing labor shortages and improving efficiency in the agricultural supply chain. Although manual grading is still widely practiced, it is often slow and inconsistent (Londhe *et al.*, 2013) ^[27]. As shown

in table 2.

Recent advancements include machine vision-based grading systems. Chen *et al.* (2023) ^[9] developed a tomato grading system using multi-view imaging techniques, incorporating

image preprocessing methods such as gamma correction and Otsu thresholding in the LAB color space. Their approach achieved a classification accuracy of 96%, demonstrating the effectiveness of automated grading systems in quality assessment.

Precooling

Precooling is a vital postharvest practice aimed at rapidly removing field heat from freshly harvested produce. It slows down metabolic processes, reduces respiration and microbial activity, and extends shelf life.

Temperature plays a crucial role in regulating physiological and biochemical processes in vegetables. High field temperatures increase respiration rates and microbial growth, leading to rapid deterioration. Precooling helps reduce field heat, bringing produce to optimal storage temperatures and thereby preserving quality and delaying senescence (Zhang *et al.*, 2023) ^[64].

Different precooling methods are selected based on crop type, packaging, cooling rate, and storage conditions.

Benefits of precooling

- Reduces water loss
- Inhibits growth of spoilage microorganisms
- Slows respiration, transpiration, and ethylene production
- Reduces enzymatic activity and promotes wound healing

Types of precooling methods

Forced-Air cooling

Forced-air cooling involves drawing cold air through packed produce, significantly enhancing cooling efficiency. It can reduce cooling time up to tenfold compared to room cooling.

Hydrocooling

Hydrocooling uses chilled water to remove heat rapidly. It is highly efficient due to the higher heat conductivity of water compared to air. However, sanitation is critical to prevent microbial contamination.

Vacuum cooling

Vacuum cooling reduces pressure, causing moisture to evaporate and absorb heat, thereby cooling the produce. It is highly effective for leafy vegetables but not suitable for waxy or dense produce. Hydro-vacuum systems help minimize moisture loss.

Ice cooling

Ice cooling maintains low temperatures during storage and transport. While effective, it may cause freezing injury, excess moisture, and increased transportation costs.

According to Tao *et al.* (2024) ^[57], various precooling methods including natural convection, slightly acidic electrolyzed water, fluid ice, cold water, vacuum cooling, and strong wind cooling significantly influence the cooling rate and visual quality of bok choy during storage.

The higher weight loss observed in bok choy treated with natural convection pre-cooling may be attributed to the longer cooling duration, the vapor pressure gradient between the produce and the surrounding environment, and increased transpiration and respiration due to retained field heat.

A gradual decline in water content during storage was observed, which can be attributed to moisture loss through respiration and the influence of ambient relative humidity. During the initial stage of storage, the moisture content in all

pre-cooled treatments was higher than that of the room temperature control, indicating that pre-cooling followed by low-temperature storage effectively reduces moisture loss. After 9 days of storage, samples treated with vacuum pre-cooling and strong wind pre-cooling maintained relatively higher moisture levels, suggesting that these methods effectively suppress transpiration and respiration, thereby delaying moisture loss during storage.

Vacuum Pre-Cooling (VPC) has proven to be highly effective for bok choy, likely due to its rapid decompression process, which disrupts microbial activity and exerts a partial sterilization effect. Bok choy subjected to VPC exhibited superior quality attributes, including better color retention, higher firmness, chlorophyll content, titratable acidity, vitamin C, total phenolics, soluble sugars, and enhanced enzymatic activities such as superoxide dismutase, ascorbate peroxidase, and catalase. Among the different pre-cooling methods, vacuum pre-cooling was found to be the most effective, as it maintained maximum firmness throughout the storage period, with the highest firmness recorded after 15 days.

Precooling of potatoes at high relative humidity (90-95%) is also recommended, as it helps reduce skin dehydration and improves overall moisture retention. studied the effects of pre-cooling potatoes for 48 hours at different temperatures (6 °C, 8 °C, and 10 °C) and relative humidity levels (87%, 91%, and 95%). Their findings indicated that pre-cooling significantly improved quality retention during subsequent cold storage.

Impact of precooling on shelf life and quality

Precooling plays a critical role in extending the shelf life and maintaining the quality of perishable vegetables. By rapidly lowering the temperature immediately after harvest, pre-cooling methods such as hydrocooling, forced-air cooling, and vacuum cooling reduce respiration rates and microbial activity, thereby slowing down deterioration processes. This helps preserve important quality attributes such as firmness, color, and nutritional value.

Effective pre-cooling not only extends shelf life but also ensures that vegetables reach consumers in optimal condition, thereby reducing postharvest losses and improving marketability.

Hydrocooling, forced-air cooling, and Vacuum Cooling (VC) have demonstrated positive effects on the cooling of cellular food systems (Alabi *et al.*, 2021) ^[68]. Kochhar and Kumar (2015) ^[70] reported that hydrocooling reduced physiological weight loss and shriveling in broccoli during storage. Similarly, forced-air cooling significantly improved the color and firmness of broccoli after 15 days of storage. Vacuum cooling has also been found effective in preserving the quality of porous vegetables such as broccoli (Carlos *et al.*, 2018) ^[71] and pak choi (Zhu *et al.*, 2020) ^[72].

Recent advances in cooling techniques

Hydrocooling

Hydrocooling is highly effective for preserving vegetables, particularly under hot climatic conditions. It rapidly removes field heat, reduces respiration, and delays postharvest deterioration (Shen *et al.*, 2012; Ribeiro *et al.*, 2018) ^[73, 74]. Additionally, it helps in cleaning produce by removing dirt and contaminants (Elansari, 2009) ^[75]. Studies have shown that hydrocooling delays wilting and reduces water loss in crops like lettuce and rockmelon (Zainal *et al.*, 2019) ^[76].

It is suitable for commodities with varying surface-to-volume ratios and has been shown to improve the color of cucumber and the quality of amaranth (Chepngeno *et al.*, 2015; Elsisi *et al.*, 2020)^[77, 78]. However, improper water temperature management may cause chilling injury, especially below 6 °C (Cantre *et al.*, 2017)^[79]. Furthermore, the use of contaminated water can introduce microbial hazards (Gleice *et al.*, 2019)^[80].

Forced-Air Cooling

Forced-air cooling is a widely adopted technique in horticulture, significantly influencing cooling rate, product quality, and energy efficiency (Kochhar and Kumar, 2015)^[70]. The cooling efficiency depends on factors such as product size, geometry, and cellular structure. Larger products tend to cool more slowly due to longer heat transfer pathways, whereas smaller products cool more rapidly (Alabi *et al.*, 2020)^[69].

Environmental factors such as air temperature, velocity, and relative humidity within the cooling chamber also play a critical role in determining cooling effectiveness (Han *et al.*, 2017)^[83]. Recent advancements using computational fluid dynamics (CFD) have improved the understanding of airflow distribution and temperature patterns, leading to enhanced cooling system design. Current research focuses on optimizing airflow patterns and packaging design to achieve uniform cooling while minimizing energy consumption (Jia *et al.*, 2026)^[84].

Modified atmosphere vacuum cooling (MAVC)

Vacuum cooling is an efficient technique for rapidly reducing the temperature of porous vegetables by evaporative cooling under reduced pressure (Song *et al.*, 2016)^[85]. When combined with modified atmosphere conditions such as reduced oxygen (O₂) and increased carbon dioxide (CO₂) it further enhances cooling efficiency and suppresses microbial activity.

Modified Atmosphere Vacuum Cooling (MAVC) has shown promising results in preserving leafy vegetables by maintaining optimal gas composition. Typically, a gas mixture of 7% O₂, 7% CO₂, and 86% N₂ is used to enhance storage quality (Zhu *et al.*, 2018)^[72]. This method effectively preserves color, vitamin C content, and reduces respiration rates in vegetables such as flowering cabbage, Chinese cabbage, and green cabbage during storage at 4 °C for up to 21 days.

However, MAVC is less effective for vegetables with thick skins or low surface area-to-volume ratios, such as tomatoes and okra. Despite its advantages, the high cost of implementation remains a limitation, and further research is required to optimize its commercial application.

The higher weight loss observed in bok choy treated with natural convection pre-cooling may be attributed to the longer precooling duration, the vapor pressure gradient between the produce and the surrounding environment, and increased transpiration and respiration due to retained field heat. A decreasing trend in water content during storage was observed, which can be attributed to moisture loss resulting from respiration and the influence of environmental relative humidity. During the early stage of storage, the moisture content in all experimental groups was higher than that of the room temperature group, indicating that precooling followed by low-temperature storage effectively reduces moisture loss. After 9 days of storage, the moisture content of the samples

treated with vacuum precooling and strong wind precooling remained relatively high, suggesting that these methods effectively inhibit transpiration and respiration, thereby delaying moisture loss during storage.

Vacuum precooling (VPC) has been shown to be highly effective for bok choy, likely due to its rapid decompression process, which disrupts microbial structures and exerts a partial sterilization effect. Bok choy treated with VPC exhibited superior quality attributes, including better color retention, higher firmness, chlorophyll content, titratable acidity, vitamin C, total phenolics, soluble sugars, and enhanced enzymatic activities such as superoxide dismutase, ascorbate peroxidase, and catalase. Among the various precooling methods, vacuum precooling proved to be the most effective, maintaining the highest level of firmness throughout the storage period, with maximum firmness observed after 15 days.

Precooling of potatoes at high relative humidity (90-95%) is recommended, as it reduces skin dehydration and improves overall moisture retention. Reported that potatoes precooled for 48 hours at different temperatures (6 °C, 8 °C, and 10 °C) and relative humidity levels (87%, 91%, and 95%) exhibited better quality retention during subsequent storage. Their analysis confirmed that precooling significantly improved the storage quality of potatoes.

Impact of precooling on shelf life and quality

Precooling plays a crucial role in extending the shelf life and maintaining the quality of perishable vegetables. By rapidly reducing the temperature immediately after harvest, precooling methods such as hydrocooling, forced-air cooling, and vacuum cooling help minimize respiration rates and microbial growth, thereby slowing deterioration. This process preserves key quality attributes such as firmness, color, and nutritional content.

Effective precooling not only extends shelf life but also ensures that vegetables reach consumers in optimal condition, thereby reducing postharvest losses and improving marketability.

Hydrocooling, forced-air cooling, and Vacuum Cooling (VC) have shown positive effects on the cooling processes of cellular foods (Alabi *et al.*, 2021)^[68]. Kochhar and Kumar (2015)^[70] reported that hydrocooling reduced physiological weight loss and shriveling in stored broccoli. Similarly, forced-air cooling significantly improved the color and firmness of broccoli after 15 days of storage. Vacuum cooling has also been found effective in preserving the quality of porous vegetables such as broccoli (Carlos *et al.*, 2018)^[71] and pak choi (Zhu *et al.*, 2020)^[72].

Recent advances in cooling techniques

Hydrocooling

Hydrocooling is highly effective for preserving vegetables, particularly under hot climatic conditions. It rapidly reduces temperature, maintains quality, and extends shelf life (Shen *et al.*, 2012)^[73]. This method uses chilled water or ice to remove field heat, slow respiration, and minimize postharvest deterioration (Ribeiro *et al.*, 2018)^[74]. Additionally, it helps cleanse produce by removing dirt and contaminants (Elansari, 2009)^[75].

Studies have shown that hydrocooling effectively delays wilting and reduces water loss in crops such as lettuce and rockmelon (Zainal *et al.*, 2019)^[76]. It is suitable for commodities with varying surface-to-volume ratios and has

been shown to improve cucumber color and amaranth quality (Chepngeno *et al.*, 2015; Elsis *et al.*, 2020) ^[77, 78]. However, water temperature must be carefully controlled, as temperatures below 6 °C may cause chilling injury (Cantre *et al.*, 2017) ^[79]. Furthermore, the use of contaminated water can introduce microbial hazards (Gleice *et al.*, 2019) ^[80].

Forced-Air Cooling

Forced-air cooling is a widely used technique for cooling horticultural produce, significantly influencing cooling rate, product quality, and energy efficiency (Gong *et al.*, 2021) ^[82]. Cooling performance depends on product size, geometry, and cellular structure. Larger products cool more slowly due to longer heat transfer distances, whereas smaller products cool more rapidly (Alabi *et al.*, 2020) ^[69].

Air properties such as temperature, velocity, and relative humidity within the cooling chamber also affect cooling efficiency (Han *et al.*, 2017) ^[83]. Advances in computational fluid dynamics (CFD) have enhanced understanding of airflow patterns and temperature distribution during cooling processes. Recent research focuses on optimizing airflow patterns and packaging design to achieve uniform cooling while reducing energy consumption (Jia *et al.*, 2021) ^[84].

Modified Atmosphere Vacuum Cooling (MAVC)

Vacuum cooling is an efficient technique for rapidly cooling porous food materials by evaporative cooling under reduced pressure (Song *et al.*, 2016) ^[85]. When combined with modified atmosphere conditions such as increased carbon dioxide (CO₂) and reduced oxygen (O₂) it further enhances cooling efficiency and reduces microbial activity.

Modified Atmosphere Vacuum Cooling (MAVC) has shown promising results for leafy vegetables by optimizing gas composition to enhance quality preservation (Zhu *et al.*, 2018) ^[72]. Typically, a gas mixture of 7% O₂, 7% CO₂, and 86% N₂ is used. This method effectively preserves color, vitamin C content, and reduces respiration rates in vegetables such as flowering cabbage, Chinese cabbage, and green cabbage during storage at 4 °C for up to 21 days.

However, MAVC is less suitable for vegetables with thick skins or low surface area-to-volume ratios, such as tomatoes and okra. Despite its effectiveness, the high cost of implementation remains a limitation, and further research is needed to optimize this technology.

Postharvest treatments

Postharvest treatments are essential for extending shelf life, maintaining quality, and reducing losses due to spoilage and decay. These treatments are applied immediately after harvest to slow physiological processes and protect produce from physical damage, pests, and diseases. Studied the effect of salicylic acid (SA) (5, 7.5, and 10 mM) and putrescine (PUT) (1, 2, and 3 mM) on immature bitter melon fruits (16 days after pollination). Fruits were dipped for 15 minutes and stored at 10 °C with 85-95% relative humidity for 20 days. The lowest decay loss was observed in fruits treated with PUT (2 and 3 mM) and SA (7.5 and 10 mM). Among all treatments, 10 mM SA showed the best results, maintaining higher total phenols (26.28 mg GAE/100 g), antioxidant activity (27.95%), ascorbic acid (50.0 mg/100 g FW), and total chlorophyll (0.32 mg/g FW), thereby improving overall quality and shelf life. Reported that calcium lactate (50, 75, and 100 mM) treatments improved the shelf life and quality of bitter melon stored at 10 °C and 85-95% RH. The 100 mM

treatment minimized physiological weight loss and decay, while maintaining higher firmness, phenolics, antioxidants, and chlorophyll content. The 75 mM treatment was effective in retaining ascorbic acid. Overall, calcium lactate at 100 mM extended shelf life up to 20 days compared to 15 days in untreated fruits.

Wang *et al.* (2018) ^[60] reported that 8 mmol/L putrescine treatment significantly delayed senescence in cowpea during cold storage by reducing weight loss and preserving ascorbic acid, chlorophyll, and phenolic content. It also enhanced antioxidant enzyme activities (POD, CAT, APX) and inhibited PPO activity.

Fang *et al.* (2022) ^[15] demonstrated that a combined chitosan and tea polyphenol (CTS+TP) coating significantly improved the postharvest quality of broccoli. This treatment reduced decay, weight loss, and respiration rate, while preserving chlorophyll, vitamin C, antioxidant capacity, and sensory attributes. It also enhanced sulforaphane content and related gene expression.

Suwannarak *et al.* (2015) ^[55] reported that a combination of 0.5% calcium chloride and chitosan coating effectively preserved the quality of carved vegetables such as pumpkin, cantaloupe, and carrot, while tap water treatment was more suitable for radish and cucumber.

Oz and Akyol (2020) ^[33] found that calcium chloride treatment, alone or combined with starch-glycerin coating, significantly improved the postharvest quality of radish stored under modified atmosphere packaging. It enhanced firmness, reduced physiological disorders, and maintained membrane integrity.

Patil *et al.* (2024) ^[36] studied the combined effect of Modified Atmosphere Packaging (MAP) and organic acid treatments on broccoli microgreens stored at 5 °C. Treatment with ascorbic acid and citric acid (0.25% each) under MAP conditions (15% CO₂, 5% O₂) significantly improved total phenolics (1247.68 mg GAE/100 g FW), flavonoids (56.9 mg QE/100 g FW), chlorophyll (42.12 mg/100 g FW), antioxidant activity, and overall quality, while reducing microbial load and weight loss. This approach extended shelf life up to 12 days.

Packaging

Packaging of vegetables plays a critical role in maintaining their quality, extending shelf life, and ensuring safe transportation from farm to consumer. Proper packaging protects vegetables from physical damage, contamination, and environmental factors such as humidity and temperature, thereby preserving freshness and improving marketability.

Functions of packaging materials

Packaging materials perform several important functions in postharvest management. They provide protection against physical damage, contamination, and environmental factors such as moisture, light, and oxygen. Packaging also helps in preservation by reducing spoilage through control of moisture loss and gas exchange. It ensures containment of produce into convenient units for handling and distribution, minimizing empty space. Additionally, packaging provides essential information such as nutritional details, usage instructions, and expiration dates. It enhances convenience through easy handling and user-friendly features, supports marketing through attractive design and labeling, ensures safety through tamper-evident features, and promotes sustainability by using recyclable and biodegradable materials.

Types of packaging materials

Packaging materials used for vegetables can be broadly classified into traditional and modern materials, each having specific advantages depending on the type of commodity and storage conditions.

Traditional packaging materials

Traditional packaging materials such as wooden boxes and sacks have long been used for transporting and storing vegetables. Wooden boxes are known for their strength and durability, providing effective protection against mechanical damage and environmental stress. Sacks made from materials like burlap or canvas are economical and breathable, making them suitable for commodities that require ventilation. Natural fiber sacks are biodegradable and environmentally friendly, whereas synthetic sacks pose environmental concerns due to their non-biodegradable nature.

Modern packaging materials

Modern packaging materials include corrugated fibreboard boxes, plastic bags, net bags, trays with overwrap, punnets, foam sleeves, and shrink wraps. Corrugated fibreboard boxes are widely used due to their lightweight nature, strength, and cushioning properties, and they are also recyclable. Plastic bags are flexible, moisture-resistant, and convenient, although they raise environmental concerns due to their non-biodegradable nature. Shrink wrap provides a tight, protective, and tamper-evident seal around products, helping to reduce contamination and extend shelf life. Despite their advantages, the environmental impact of plastic-based materials has led to increasing interest in biodegradable alternatives.

Advanced Packaging Techniques

Advanced packaging techniques have significantly improved the postharvest handling of vegetables by enhancing shelf life and maintaining quality through better control of internal package conditions.

Modified Atmosphere Packaging (MAP)

Modified Atmosphere Packaging (MAP) is an important technique used to extend the shelf life of vegetables by altering the gaseous composition within the package. It works by reducing oxygen (O₂) levels and increasing carbon dioxide (CO₂) concentrations, thereby slowing respiration and microbial activity. Typically, MAP uses combinations of O₂, CO₂, and nitrogen (N₂), where for respiring products, around 5% O₂ and 5% CO₂ are maintained to reduce metabolic activity. MAP has been shown to effectively preserve quality attributes such as firmness, color, and nutritional value in various vegetables. For example, cherry tomatoes packed in MAP maintained better firmness and vitamin C content under optimized gas conditions. Similarly, amaranth stored under MAP retained higher ascorbic acid and quality (Nyaura *et al.*, 2014; Jin *et al.*, 2021) [32, 23]. Studies on cucumber and bitter melon also demonstrated reduced weight loss and improved sensory quality under MAP conditions (Singh *et al.*, 2024; Preetha *et al.*, 2016; Pinto *et al.*, 2020; Roopnarine and Mohammed, 2021) [40, 51, 88, 89].

Classification of MAP

Modified Atmosphere Packaging can be classified into passive and active systems. In passive MAP, the internal atmosphere is modified naturally by the respiration of the produce after sealing the package. In contrast, active MAP

involves flushing the package with a predetermined gas mixture before sealing, allowing precise control over the internal gaseous composition.

Recent Innovations in MAP

Recent innovations in MAP include the development of smart packaging systems equipped with sensors that monitor and regulate gas composition in real time. Advances in micro-perforation technology have enabled precise control of gas exchange, improving storage efficiency. Additionally, the development of biodegradable and eco-friendly packaging materials is gaining importance to reduce environmental impact and enhance sustainability.

Active packaging

Active packaging is an advanced technology in which packaging materials interact with the product to extend shelf life and maintain quality. This system may include gas scavengers, antimicrobial agents, and antioxidants that help control microbial growth and oxidative processes (Ozdemir and Floros, 2004) [34]. While sachet-based systems are effective, they may pose risks such as accidental ingestion and potential toxicity. Therefore, active films and coatings are increasingly preferred due to their improved safety, efficiency, and consumer acceptance.

Packaging requirements for fresh produce

Effective packaging of fresh vegetables must fulfill several essential requirements. It should provide protection against microbial contamination and deterioration, prevent bruising and mechanical injury, and minimize moisture and weight loss. Packaging should also allow adequate ventilation for respiration and gas exchange, regulate ethylene concentration, and slow down metabolic processes such as respiration and ripening (Siddiqui *et al.*, 2021) [90]. By meeting these requirements, packaging plays a vital role in extending shelf life, maintaining quality, and improving the marketability of fresh produce.

Components of active packaging

Active packaging consists of several functional components that interact with the packaged produce to extend shelf life and maintain quality by controlling internal environmental conditions.

Oxygen control

Oxygen plays a significant role in the spoilage of fresh produce by promoting oxidative degradation and microbial growth. Active packaging systems utilize oxygen absorbers to reduce oxygen levels within the package, thereby slowing these deteriorative processes. For many oxygen-sensitive products such as lettuce and potatoes, oxygen levels below 1% are essential to prevent enzymatic browning and spoilage caused by polyphenol oxidation (Charles *et al.*, 2003) [8]. Oxygen absorbers are a key component of active Modified Atmosphere Packaging (MAP), incorporating both gas-scavenging and gas-flushing techniques to create an optimal internal environment (Charles *et al.*, 2003) [8]. These absorbers effectively reduce oxygen partial pressure and remove any oxygen entering from outside the package.

Various oxygen scavenging agents are used, including enzymes like glucose oxidase, reactive metals such as iron and zinc, and ascorbic acid-based compounds (vitamin C). Among these, iron-based absorbers are widely used in sachet form due to their high efficiency. Iron carbonate reacts with oxygen and moisture through oxidation, effectively removing

oxygen from the package headspace. Studies have demonstrated their effectiveness; for example, Charles *et al.* (2003)^[8] reported extended shelf life of tomatoes using iron-based absorbers. Similarly, Eshpari, 2011^[91] found that oxygen absorbers combined with high-barrier polypropylene and nylon laminate films preserved β -carotene in dried sweet potato chips for more than 210 days.

Ethylene control

Ethylene is a natural plant hormone that regulates ripening, senescence, color development, and volatile production in fruits and vegetables (Ozdemir and Floros, 2004)^[34]. Although essential for physiological processes, excess ethylene accelerates ripening and deterioration, particularly in climacteric fruits, thereby reducing shelf life. Vegetables are generally less sensitive to ethylene compared to fruits but its accumulation still negatively affects quality during storage.

To mitigate these effects, active packaging incorporates ethylene scavengers that remove or reduce ethylene concentration within the package. These scavengers are available in various forms such as sachets, films, paper, and cardboard materials. Common substances used include potassium permanganate, activated carbon, and mineral substrates. Potassium permanganate oxidizes ethylene into acetaldehyde and ethanol, while carbon-based materials absorb and degrade ethylene (Coles *et al.*, 2003)^[11].

The effectiveness of ethylene scavengers has been demonstrated in several studies. Esturk *et al.* (2014)^[92] reported that broccoli stored in LDPE films containing zeolite-based ethylene scavengers maintained better quality, including higher total soluble solids, phenolic content, chlorophyll, and reduced weight loss during 20 days of storage at 4 °C. In contrast, broccoli stored without scavengers experienced rapid quality deterioration due to anaerobic conditions, with oxygen levels dropping below 1% and ethylene concentration rising to 61.8 ppm.

Moisture control

Moisture control is essential in maintaining the quality of fresh fruits and vegetables, as both excess and insufficient moisture can lead to spoilage. Fresh produce generally requires a relative humidity of 85-95% to prevent dehydration and microbial growth. Active packaging systems regulate moisture levels using humidity absorbers or desiccants that either absorb excess moisture or release it when needed. Common moisture absorbers include sorbitol, sodium chloride, potassium chloride, and bentonite (Rux *et al.*, 2016)^[45]. Fast-acting absorbers such as sodium chloride, potassium chloride, and sorbitol quickly remove excess moisture, while bentonite provides slower, sustained absorption. Deliquescent salts like sodium chloride can absorb moisture at high humidity levels and release it when humidity decreases, thereby acting as effective humidity buffers (Rux *et al.*, 2016)^[45].

Several studies highlight the benefits of moisture control systems. Shirazi and Cameron (1992)^[49] reported that tomatoes stored in LDPE films with sodium chloride absorbers showed a shelf life extension of 10-12 days. Similarly, found that a combination of calcium chloride, sorbitol, and bentonite improved the sensory quality and appearance of mushrooms during storage at 10 °C. However, the selection of moisture absorbers depends on factors such as commodity type, packaging material permeability, storage

Conditions, and initial humidity levels (Coles *et al.*, 2003)^[11].

Freshness indicators and RFID tags

Freshness indicators are used to monitor chemical and microbial changes within packaged food by detecting metabolites such as carbon dioxide, oxygen, ethanol, and organic acids. These indicators often require direct contact with food and must comply with food safety regulations. Products like Food Fresh™ use color-changing polyethylene terephthalate (PET) materials to indicate product freshness over time (Mohebi and Marquez, 2015)^[30].

RFID (Radio Frequency Identification) tags are advanced tools used for monitoring and tracking packaged products. These devices operate using electromagnetic fields and can transmit data through a reader. RFID tags are classified into passive, semi-passive, and active types, depending on their power source and functionality. They enhance traceability, inventory management, and quality monitoring in the supply chain.

Antimicrobial packaging

Antimicrobial packaging incorporates agents that inhibit the growth of spoilage-causing microorganisms, thereby extending shelf life and improving food safety. These agents can be classified as volatile or non-volatile. Non-volatile agents, such as organic acids, enzymes, and polysaccharides, require direct contact with the food surface, while volatile agents like ethanol and essential oils act through the package atmosphere (Siddiqui *et al.*, 2018)^[50].

Various studies demonstrate the effectiveness of antimicrobial packaging. Seo *et al.* (2012)^[47] reported significant reduction of *E. coli* in spinach using allyl isothiocyanate sachets. Murriel *et al.* found oregano essential oil incorporated in films effective against major foodborne pathogens. showed that silver nanoparticle pads reduced microbial load and improved quality in fresh-cut melon. However, the use of natural antimicrobial agents such as essential oils must be carefully managed due to their strong sensory effects (Burt, 2004; Antunes and Cavaco, 2010)^[95, 96].

Intelligent packaging

Intelligent packaging systems are designed to monitor the condition and quality of food without directly altering the internal environment (Yam, 2012)^[97]. These systems provide real-time information about product status by detecting changes in internal and external conditions. Common components include indicators, sensors, and data carriers such as RFID tags (Ghaani *et al.*, 2016)^[18].

Freshness indicators are widely used in fruits and vegetables to detect pH changes associated with spoilage.

Edible packaging

Edible packaging provides a sustainable alternative to conventional packaging by forming a protective, consumable barrier around food products. These coatings are made from biopolymers and help control moisture loss, gas exchange, and microbial contamination, thereby extending shelf life and maintaining quality.

Edible coatings have been widely studied for their effectiveness. Sree *et al.* (2020)^[52] reported that 2.5% chitosan coating significantly extended the shelf life of tomatoes up to 30 days while delaying ripening. Similarly, Das *et al.* (2022)^[12] demonstrated that a bionanocomposite

coating of carboxymethyl cellulose and cardamom essential oil reduced weight loss and maintained quality in tomatoes during storage. Despite their benefits, further research is needed to address regulatory, safety, and large-scale application challenges.

Storage

Storage of vegetables is a critical component of postharvest management, as it directly affects shelf life, quality, and nutritional value. The primary objective of storage is to maintain freshness and minimize spoilage by controlling temperature, relative humidity, and atmospheric composition.

Controlled Atmosphere (CA) and Modified Atmosphere (MA) storage are widely used techniques to enhance storage life. Controlled atmosphere storage involves continuous regulation of gas composition, whereas modified atmosphere storage involves initial modification followed by gradual changes due to respiration and packaging permeability (Jayas and Jeyamkondan, 2002) [99]. Lowering oxygen levels and increasing carbon dioxide concentrations reduces respiration and metabolic activity, thereby slowing senescence and extending shelf life.

Temperature control

Temperature control is a crucial factor in postharvest storage, as it directly influences the shelf life, quality, and physiological processes of vegetables. Different vegetables exhibit varying levels of chilling sensitivity, and while low temperatures help in reducing respiration and delaying spoilage, excessively low temperatures may cause chilling injury in sensitive crops. For instance, leafy vegetables such as spinach are highly susceptible to chilling injury and show symptoms within a short exposure period, whereas crops like tomato can tolerate low temperatures for a longer duration before exhibiting such injuries.

The study conducted by Iwuagwu and Ezeufoh (2024) [21] evaluated the effect of different storage methods on the quality of okra fruits in Nigeria. The experiment involved storing freshly harvested okra in woven baskets lined with bitter leaves, unlined baskets, perforated paper cartons lined with bitter leaves, and unlined cartons. The results indicated that packaging materials significantly affected the physical quality and moisture content of okra, with unlined cartons showing a higher number of healthy fruits and better moisture retention compared to other storage methods.

Similarly, Pholsin *et al.* investigated the impact of transport distance, storage temperature, and duration on tomato weight loss. Their findings revealed that weight loss increased with longer transport distances and higher storage temperatures. Tomatoes stored at 22 °C for 12 days showed the highest weight loss, reaching up to 6.91% for long-distance transport, whereas storage at 10 °C significantly reduced weight loss across all distances, ranging from 3.09% to 3.5%. The study concluded that low-temperature storage effectively minimizes transpiration and respiration rates, thereby reducing dehydration and maintaining product quality.

Weight loss in vegetables during storage is primarily caused by transpiration and respiration processes. Higher temperatures increase vapor pressure deficits, leading to accelerated moisture loss and shriveling, which ultimately reduces market acceptability. Conversely, low-temperature storage minimizes these processes and helps in maintaining water balance within the produce.

Jany *et al.* (2008) [22] studied the effect of different storage temperatures on vegetables such as cabbage, cauliflower, country bean, tomato, and pea. The vegetables were stored at room temperature (for 8 days), refrigerated conditions at 4 °C (for 12 days), and freezing conditions at -18 °C (for 90 days). The results indicated that color, flavor, and texture were best preserved under freezing conditions. Additionally, vitamin C content varied across storage conditions, with freezing retaining higher levels compared to room and refrigerated storage. However, weight loss increased progressively over time in all storage conditions.

Wei *et al.* (2019) [61] reported that fresh-cut broccoli treated with 100 µM melatonin and stored at 4 °C with 95% relative humidity for 25 days showed enhanced antioxidant activity. The treatment effectively regulated antioxidant compounds such as ascorbic acid, total phenols, and flavonoids, thereby improving the storage quality of broccoli.

Future prospects

The future of postharvest management lies in the adoption of smart, sustainable, and technology-driven solutions. Innovations such as nanotechnology-based edible coatings, advanced MAP systems, plasma technology, High-Pressure Processing (HPP), and Pulse Electric Fields (PEF) are expected to play a major role in enhancing shelf life and maintaining quality. The integration of digital tools such as Artificial Intelligence (AI), Internet of Things (IoT), blockchain technology, and predictive analytics will enable real-time monitoring, improved traceability, and efficient supply chain management.

Additionally, the development of intelligent packaging systems, smart sensors, and automation in sorting and grading will further improve postharvest handling. Sustainable approaches, including biodegradable packaging materials and the utilization of agro-waste for bioplastics and biofertilizers, will contribute to environmental conservation and resource efficiency.

Challenges

Despite significant advancements, several challenges limit the widespread adoption of modern postharvest technologies. High initial investment costs and lack of adequate cold chain infrastructure remain major constraints, particularly in developing countries. Limited technical knowledge, lack of skilled manpower, and insufficient awareness among farmers and stakeholders further hinder implementation.

Regulatory issues and lack of standardization for emerging technologies, especially nanotechnology and antimicrobial agents, pose additional barriers. Consumer concerns regarding food safety, chemical residues, and potential sensory changes also affect acceptance. Furthermore, maintaining a balance between cost-effectiveness, sustainability, and technological efficiency continues to be a critical challenge in postharvest management systems.

Conclusion

In recent years, innovative postharvest technologies have played a vital role in extending the shelf life and maintaining the quality of vegetables. These advancements contribute significantly to reducing postharvest losses and improving food security by ensuring that vegetables retain their nutritional value and marketability throughout the supply chain.

The integration of modern technologies such as active and intelligent packaging, controlled storage systems, and digital tools can greatly enhance postharvest management practices. As global demand for fresh produce continues to increase, the adoption of these advanced and sustainable solutions will be essential to address food supply challenges and promote environmentally responsible agricultural practices.

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