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Postharvest Management Techniques for Improved Shelf Life of Horticultural Crops: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Postharvest management in horticulture is important for maintaining the quality, safety, and shelf life of produce, significantly impacting global food security and economic stability. This review explores critical advancements in postharvest practices, focusing on quality control, safety standards, and emerging technologies. Postharvest quality assessment involves the evaluation of physical, chemical, and sensory attributes, supported by microbiological testing to ensure food safety. Global standards like HACCP, GlobalG.A.P., and ISO 22000 provide frameworks for ensuring compliance and market access. Technological innovations, including near-infrared spectroscopy, hyperspectral imaging, and smart sensors, enable precise, real-time monitoring of produce quality, enhancing

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operational efficiency. Emerging technologies are revolutionizing the field; nanotechnology offers advanced packaging solutions that improve shelf life and food safety, while drones and AI enhance postharvest monitoring and logistics through real-time data collection and predictive analytics. Blockchain technology introduces unprecedented levels of traceability and transparency, ensuring accountability and rapid response to food safety issues. The integration of these technologies not only improves the efficiency and sustainability of postharvest systems but also aligns with consumer demands for high-quality, safe, and sustainably sourced produce. This holistic approach reduces post- harvest losses, enhances market competitiveness, and contributes to global efforts in ensuring food security. The synergy of traditional quality control methods with cutting-edge technologies paves the way for a resilient and adaptive post- harvest management system that meets the evolving challenges of the agricultural sector.

Keywords: Postharvest; quality control; safety standards; nanotechnology; hyperspectral imaging.

1. INTRODUCTION

The significance of postharvest management in horticulture lies at the core of ensuring the quality, longevity, and marketability of horticultural produce, which includes fruits, vegetables, flowers, and other perishable commodities. These crops are highly vulnerable to rapid deterioration postharvest due to their high moisture content and metabolic activity. Effective postharvest management encompasses a range of practices and technologies designed to minimize losses and maintain the quality of produce from the point of harvest to consumption (Kader & Rolle, 2004). This is critical not only for preserving the nutritional and sensory qualities of horticultural produce but also for reducing economic losses and enhancing food security globally.

1.1 Postharvest Management in Horticulture

Horticultural crops are characterized by their perishability and sensitivity to environmental factors such as temperature, humidity, and mechanical damage. Without appropriate postharvest management, these crops are prone to significant losses. Postharvest management plays a vital role in extending the shelf life of produce, thereby reducing waste and ensuring that a larger proportion of harvested crops reach consumers in optimal condition (El-Ramady et al., 2015). Practices such as proper harvesting, sorting, cleaning, cooling, storage, and packaging are crucial in maintaining the quality and safety of horticultural products. One of the primary reasons for the importance of postharvest management is its impact on reducing postharvest losses. These losses have far-reaching implications not only for the economic well-being of farmers and other stakeholders in the supply chain but also for the availability and affordability of nutritious food for consumers. By implementing effective postharvest management practices, it is possible to significantly reduce these losses, thereby improving food availability and contributing to the livelihoods of those involved in the horticulture sector.

1.2 Postharvest Losses on Global Food Security

Postharvest losses represent a significant challenge to global food security, particularly in the context of a growing global population and the increasing demand for food. Around one-third of all food produced globally is lost or wasted each year, with postharvest losses accounting for a substantial proportion of this figure, especially in the case of fruits and vegetables (Fig. 2) (Bourne, 1977). These losses translate into reduced food availability, higher food prices, and increased pressure on natural resources such as land, water, and energy. The impact of postharvesty losses is particularly pronounced in developing countries, where inadequate infrastructure, poor handling practices, and lack of access to appropriate technologies exacerbate the problem. Sub-Saharan Africa, postharvest losses of fruits and vegetables could reach up to 50%, significantly undermining food security and economic development in the region (Fig. 1). Developed countries tend to experience lower postharvest losses due to better infrastructure and advanced technologies, but food waste at the consumer level remains a major issue. Addressing postharvset losses is critical for enhancing global food security. By reducing these losses, it is possible to increase the availability of nutritious food without the need for additional agricultural production, thereby reducing the pressure on natural resources and contributing to environmental sustainability (Koning et al., 2008). Moreover, reducing postharvest losses can help to stabilize food prices and improve the incomes of smallholder farmers, who are often the most affected by postharvest losses.

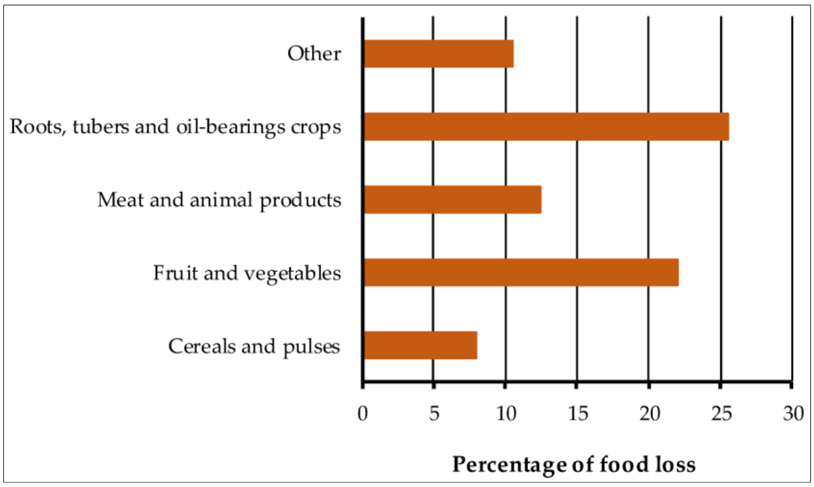

Fig. 1. Food losses and waste along the supply chain (percentage for each food group)

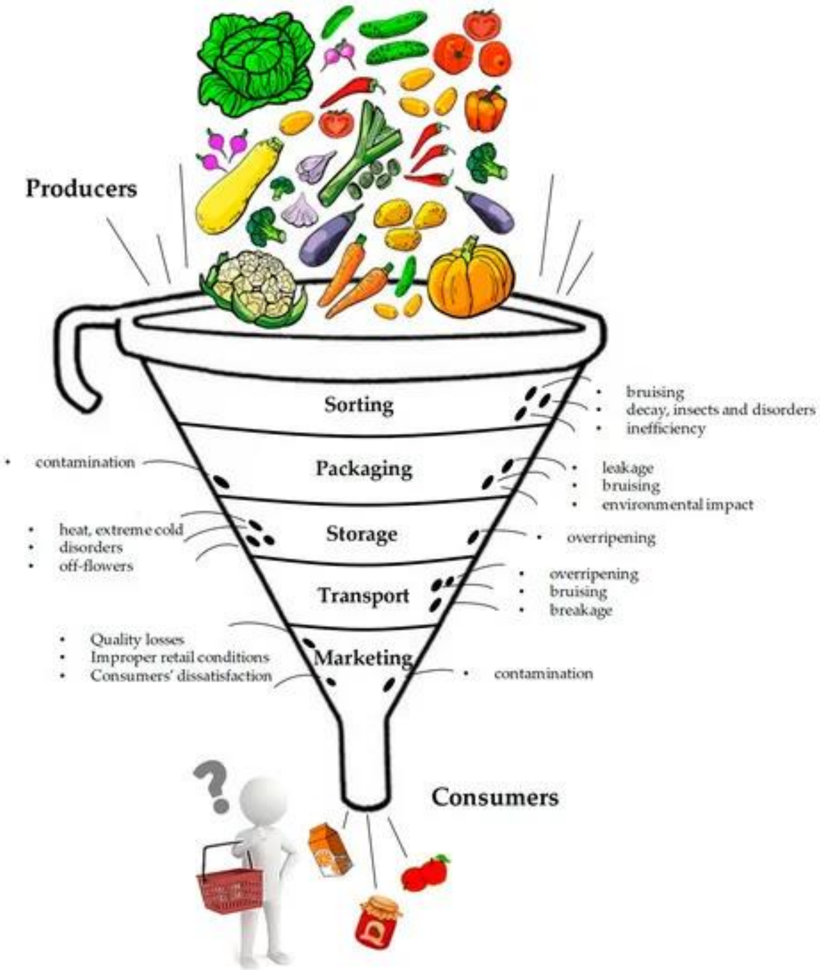

Fig. 2. Causes of postharvest losses along the supply chain
Source- (Bourne, 1977)

1.3 Objective and Scope of the Review

The primary objective of this review is to provide a comprehensive analysis of the various postharvest management techniques that have been developed to improve the shelf life of horticultural crops. The review will synthesize existing knowledge on a wide range of topics, including the physiological and biochemical changes that occur in horticultural produce postharvest, the latest advancements in storage and transportation technologies, and the role of regulatory frameworks in ensuring the quality and safety of produce. The scope of the review encompasses both traditional and emerging postharvest management practices. It will explore innovative technologies such as controlled atmosphere storage, modified atmosphere packaging, and the use of biocontrol agents and bio-preservatives (Muthuvelu et al., 2023). The review will examine the integration of cutting-edge technologies such as nanotechnology, artificial intelligence, and blockchain in postharvest systems. By collating and critically evaluating the existing literature, this review aims to provide insights into best practices, highlight current challenges, and propose future research directions that could further enhance the efficiency and sustainability of postharvest management in horticulture. The review will include case studies and practical applications from different regions, illustrating the real-world impact of effective postharvest management strategies. This holistic approach will provide valuable insights for researchers, policymakers, and practitioners, guiding the development of more robust and adaptive postharvest solutions that can contribute to global food security and economic development.

2. PHYSIOLOGICAL AND BIOCHEMICAL CHANGES DURING POSTHARVEST

The postharvest life of horticultural crops is intricately governed by a series of physiological and biochemical processes (Table 1) (Yahia & Carrillo-Lopez, 2018). Understanding these processes is crucial for devising strategies to extend shelf life, maintain quality, and minimize losses. The primary physiological and biochemical changes include respiration and ethylene production, water loss and desiccation, as well as nutrient degradation and flavor loss.

2.1 Respiration and Ethylene Production

Respiration is a fundamental metabolic process in postharvest horticultural crops, involving the oxidation of stored carbohydrates to produce energy in the form of ATP. This process continues after harvest, utilizing oxygen and releasing carbon dioxide and water, alongside energy (Saltveit, 2019). The rate of respiration directly influences the rate of senescence and overall shelf life of produce. High respiration rates are associated with rapid depletion of stored reserves, leading to quicker deterioration. For example, highly perishable fruits such as strawberries and spinach exhibit high respiration rates, necessitating immediate cooling after harvest to slow down metabolic activities. Ethylene, a naturally occurring plant hormone, plays a pivotal role in regulating ripening and senescence. Its production is particularly significant in climacteric fruits, such as bananas, apples, and tomatoes, which exhibit a marked increase in respiration and ethylene synthesis during ripening (Payasi & Sanwal, 2010). Ethylene not only accelerates ripening but also triggers a cascade of physiological changes including softening, color changes, and aroma development. In non-climacteric fruits like citrus and grapes, ethylene has a less pronounced role but can still induce senescence-related changes. Ethylene management through inhibitors like 1-methylcyclopropene (1-MCP) has been widely adopted to delay ripening and extend shelf life.

2.2 Water Loss and Desiccation

Water loss is another critical factor affecting postharvest quality. Horticultural crops, being rich in water, are prone to desiccation, which leads to weight loss, shriveling, and textural degradation (Saltveit, 2016). The rate of water loss is influenced by factors such as the surface area-to-volume ratio of the produce, the permeability of the cuticle, ambient humidity, and temperature. Leafy vegetables like lettuce and spinach are particularly vulnerable to rapid water loss due to their large surface area and thin cuticle. Water loss primarily occurs through transpiration, a process driven by the vapor pressure deficit between the produce and the surrounding atmosphere. High temperatures and low relative humidity accelerate this process, leading to significant post- harvest losses. Maintaining a high relative humidity in storage environments, typically around 90-95%, is crucial for minimizing desiccation. However, excessive humidity can promote microbial growth, necessitating a delicate balance. The application of coatings, such as wax or edible films, has been explored to reduce transpiration and delay desiccation. These coatings act as semipermeable barriers, reducing water vapor loss while allowing gas exchange. For instance, wax coatings on citrus fruits effectively minimize weight loss and maintain firmness during storage (Hassan et al., 2014).

2.3 Nutrient Degradation and Flavor Loss

Postharvest nutrient degradation is a significant concern, as it directly impacts the nutritional quality and marketability of horticultural produce. Vitamins, particularly vitamin C, are highly susceptible to degradation during postharvest handling and storage. Ascorbic acid (vitamin C) degradation is influenced by factors such as exposure to light, temperature, oxygen, and mechanical injury. Leafy vegetables and soft fruits are especially prone to rapid vitamin C loss, with storage temperatures above 4°C significantly accelerating the degradation process (Mampholo et al., 2016). In addition to nutrient loss, postharvest changes also affect the sensory attributes of produce, including flavor, texture, and aroma. Flavor compounds, such as sugars, organic acids, and volatile aromatic compounds, are synthesized and metabolized during ripening. For example, in tomatoes, the balance between sugars (fructose and glucose) and organic acids (mainly citric acid) determines sweetness and acidity, while volatile compounds contribute to the characteristic aroma. Postharvest handling that disrupts cellular integrity, such as mechanical damage or improper storage conditions, can lead to enzymatic degradation of these compounds, resulting in off-flavours and a decline in overall eating quality. Texture, an important sensory attribute, is determined by the structural integrity of cell walls and the turgor pressure of cells. Postharvest changes such as pectin degradation and cell wall softening are mediated by enzymes like pectin methylesterase and polygalacturonase, leading to textural changes such as softening in fruits like peaches and avocados (Sozzi, 2004). Maintaining optimal storage conditions, such as low temperatures and controlled atmospheres, is critical to slowing down these biochemical changes and preserving textural quality.

Table 1. Physiological and biochemical changes during postharvest of fruits and vegetables

Physiological/Biochemical aspect	Description	Impact on quality	Examples
Respiration Rate	Increases after harvest, leading to the breakdown of stored carbohydrates into CO_2, water, and heat.	Faster spoilage and reduced shelf life	Apples, bananas
Ethylene Production	Ethylene, a ripening hormone, accelerates maturation and senescence.	Triggers ripening, softening, and decay	Tomatoes, avocados
Water Loss (Transpiration)	Loss of water through the skin or cut surfaces, leading to weight loss and shriveling.	Reduces firmness and freshness	Leafy greens, cucumbers
Starch to Sugar Conversion	Conversion of starches into simpler sugars during ripening.	Increases sweetness, reduces texture firmness	Bananas, mangoes
Protein Degradation	Breakdown of proteins into amino acids by proteolytic enzymes.	Alters texture and flavor	Papaya, tomatoes
Chlorophyll Degradation	Breakdown of chlorophyll into non-green pigments during ripening or senescence.	Causes color changes (e.g., green to yellow)	Bananas, bell peppers
Phenolic Metabolism	Oxidation of phenolic compounds leads to browning reactions, especially in cut or damaged tissues.	Reduces visual quality, impacts taste	Apples, potatoes

Physiological/Biochemical aspect	Description	Impact on quality	Examples
Lipid Peroxidation	Oxidative degradation of lipids resulting in rancidity.	Leads to off-flavors and nutrient loss	Nuts, avocados
Vitamin C Degradation	Ascorbic acid is sensitive to oxidation, especially in cut or bruised produce.	Loss of nutritional value and antioxidant properties	Citrus fruits, strawberries
Accumulation of Secondary Metabolites	Increased synthesis of compounds like flavonoids, alkaloids, and terpenes during stress conditions.	Can enhance flavor, aroma, and defense	Grapes, herbs
Enzymatic Browning	Polyphenol oxidase activity leads to browning in cut or damaged tissues.	Affects appearance and consumer acceptability	Apples, potatoes
Pectin Degradation	Breakdown of pectin substances by pectinases results in softening.	Reduces firmness and texture	Tomatoes, peaches
Change in Organic Acids	Reduction in organic acid content as they are metabolized during respiration.	Alters taste, reduces acidity	Citrus fruits, tomatoes

(Source: Saltveit (2019), Payasi & Sanwal (2010), Sozzi (2004))

3. HARVESTING TECHNIQUES

The harvesting process marks the beginning of the post- harvest journey for horticultural crops, and the techniques used can significantly influence their shelf life, quality, and market value. The critical aspects of harvesting include determining the optimal harvesting time, selecting between manual and mechanical methods, and understanding the impact of these practices on the longevity and quality of the produce (Colledani et al., 2014).

3.1 Optimal Harvesting Time

The determination of the optimal harvesting time is crucial for ensuring that horticultural crops reach the market at their peak quality. Harvesting too early or too late can have adverse effects on the produce's shelf life, nutritional value, and sensory attributes. For instance, fruits harvested before reaching physiological maturity may not develop their full flavor, color, or size, while overripe fruits are more prone to physical damage, microbial infection, and rapid deterioration. Different crops have specific indicators for determining their optimal harvesting time. These indicators include visual cues (color, size, shape), physiological markers (firmness, sugar content, acidity), and technological tools (refractometers, firmness testers). For example, in apples, a combination of starch index, firmness, and soluble solids content is used to gauge harvest readiness (Kumar et al., 2023). Similarly, in tomatoes, the color transition from green to red is a primary indicator, often complemented by the measurement of ethylene levels. Advancements in technology have introduced non-destructive methods for determining optimal harvesting time, such as near-infrared spectroscopy (NIR) and hyperspectral imaging, which allow for the assessment of internal quality attributes without damaging the produce (Chandrasekaran et al., 2019). These innovations are increasingly being adopted to ensure precise harvesting, thereby improving postharvest quality and reducing losses.

3.2 Methods of Harvesting: Manual vs. Mechanical

Harvesting methods can be broadly categorized into manual and mechanical approaches, each with its advantages and challenges.

***Manual Harvesting*:** Traditionally, manual harvesting has been the predominant method for most horticultural crops, especially those that are delicate and prone to damage, such as berries, grapes, and leafy greens. Manual harvesting allows for selective picking based on the maturity and quality of individual fruits or vegetables. This method helps minimize physical damage and ensures that only the produce of optimal quality is harvested (Elik et al., 2019). However, manual harvesting is labor-intensive, time-consuming, and subject to human error and variability in skill levels. In regions with labor shortages or high labor costs, manual harvesting can be economically unsustainable.

***Mechanical Harvesting*:** With the advancement of agricultural technology, mechanical harvesting has gained popularity, particularly for crops like grains, root vegetables, and tree fruits, which are less susceptible to mechanical damage. Mechanical harvesters are designed to increase efficiency, reduce labor costs, and expedite the harvesting process. However, the adoption of mechanical harvesting poses challenges, such as potential damage to the produce, especially if the equipment is not properly calibrated or maintained. For instance, mechanical harvesters for fruits like apples and cherries need to be gentle enough to avoid bruising while still being efficient (Whiting & Perry, 2017).

3.3 Impact of Harvesting Practices on Shelf Life

The harvesting practices employed have a direct and profound impact on the postharvest shelf life of horticultural crops. Properly timed and executed harvesting minimizes physical damage, reduces metabolic activity, and curbs the incidence of postharvest diseases. Conversely, improper harvesting techniques can lead to mechanical injuries, such as bruising, cuts, or abrasions, which compromise the integrity of the produce, making it more susceptible to microbial infection and accelerated spoilage (Jain et al., 2023). Manual harvesting, with its selective picking approach, generally results in minimal physical damage, thus preserving the structural integrity of the produce and enhancing its shelf life. However, the efficiency and consistency of manual harvesting depend on the skill and care of the laborers, highlighting the need for proper training and supervision. Mechanical harvesting, while efficient, can increase the risk of physical damage if not properly managed. Innovations in mechanical harvesting, such as the development of fruit catchers, cushioned conveyors, and vibration-based harvesting systems, aim to reduce damage and enhance the quality of harvested produce. Integrating pre-harvest treatments, such as the application of calcium or anti-transpirants, can help strengthen the cell walls and reduce water loss, thereby improving the resilience of the produce to mechanical harvesting and extending its shelf life (Gunny et al., 2024). The postharvest handling process, including sorting, grading, and packaging, also plays a critical role in mitigating the impact of harvesting practices on shelf life. Proper handling and storage conditions, such as maintaining appropriate temperatures and humidity levels, are essential for preserving the quality of harvested produce and extending its marketable life.

4. POSTHARVEST HANDLING

Effective postharvest handling is crucial in maintaining the quality, safety, and marketability of horticultural crops (Table 2). This stage includes several key processes such as sorting and grading, cleaning, washing, and packaging innovations. These practices help reduce postharvest losses, enhance product appeal, and extend the shelf life of produce, ensuring that consumers receive fresh and high-quality products (Ahmad et al., 2015).

4.1 Sorting and Grading

Sorting and grading are fundamental postharvest handling processes that help in categorizing produce based on size, shape, color, ripeness, and the presence of defects or diseases. These processes serve multiple purposes: they enhance market value by standardizing produce, facilitate packaging and storage, and reduce the spread of decay by removing damaged or diseased items. Sorting is done manually or mechanically. Manual sorting relies on human labor to inspect and separate produce, which is effective but labor-intensive and subject to human error and inconsistency. Mechanical sorting, on the other hand, utilizes advanced technologies such as conveyor belts, cameras, and sensors to automatically sort produce. These systems are more efficient and consistent, capable of handling large volumes of produce while ensuring uniformity (Slack, 1983). Grading is closely related to sorting but focuses more on categorizing produce into specific quality classes based on standardized criteria. For example, apples grading is based on size, color, and freedom from blemishes, which helps in determining their market price and suitability for different markets. Grading not only improves the visual appeal and marketability of produce but also allows consumers to make informed choices based on quality.

Table 2. Postharvest handling of fruits and vegetables: Key processes and techniques

Post-harvest handling stage	Description	Objective	Examples
Harvesting	Optimal maturity stage for harvesting is crucial to ensure quality and reduce losses.	Maximizing shelf life and reducing damage	Hand-picking tomatoes, cutting mangoes
Cleaning and washing	Removal of dirt, pesticide residues, and microorganisms from the surface of produce.	Ensuring food safety and visual appeal	Washing lettuce, rinsing apples
Grading and sorting	Classification based on size, color, shape, and ripeness.	Enhancing market value and uniformity	Grading oranges, sorting potatoes
Pre-Cooling	Rapid cooling of harvested produce to remove field heat.	Extending shelf life and slowing respiration	Hydro-cooling of leafy greens, air-cooling berries
Packaging	Use of appropriate materials and containers to protect produce during transit.	Preventing mechanical damage and contamination	Using plastic crates for grapes, carton boxes for bananas
Storage	Maintaining produce under controlled temperature and humidity conditions.	Minimizing spoilage and prolonging freshness	Cold storage for apples, controlled atmosphere for kiwis
Transportation	Moving produce from farms to markets or processing units with minimal damage.	Ensuring quality during transit	Refrigerated trucks for strawberries, crates for tomatoes
Use of edible coatings	Application of edible, biodegradable coatings to reduce moisture loss and delay ripening.	Enhancing shelf life and appearance	Wax coatings for citrus fruits, chitosan for cucumbers
Modified Atmosphere Packaging (MAP)	Packaging in altered atmospheric conditions with reduced oxygen and increased CO_2 levels.	Extending shelf life by slowing respiration	MAP for leafy greens, pre-cut salads
Chemical treatments	Application of fungicides, ethylene inhibitors, or preservatives to reduce spoilage.	Controlling decay and ripening	Using 1-MCP for bananas, fungicides for citrus fruits
Irradiation	Use of ionizing radiation to control spoilage organisms and pests.	Enhancing safety and shelf life	Irradiation of spices, potatoes
Ripening chambers	Controlled environments to regulate temperature, humidity, and ethylene levels for uniform ripening.	Ensuring consistent ripening	Ethylene chambers for bananas, mangoes
Post-Harvest treatments	Application of techniques such as hot water dips or calcium chloride solutions to reduce spoilage.	Reducing post-harvest losses	Hot water treatment for mangoes, calcium dips for apples

(Sources: Slack (1983), Jayaraman & Gupta (2020), Rajeshkumar et al. (2021))

4.2 Cleaning and Washing

Cleaning and washing are essential steps in postharvest handling to remove soil, dust, pesticides, and microbial contaminants from the surface of produce. These processes enhance the appearance, safety, and shelf life of the produce. Proper cleaning and washing help in reducing the microbial load, thereby lowering the risk of spoilage and foodborne illnesses (Gil et al., 2015). The cleaning process typically begins with dry methods such as brushing or air blowing to remove loose dirt and debris. This is followed by washing with water or aqueous solutions containing sanitizers. The use of sanitizers like chlorine, hydrogen peroxide, and peracetic acid in wash water is common to ensure microbial safety. To prevent chemical residues on the produce and to comply with food safety regulations, concentrations of sanitizers must be carefully controlled. Advanced washing technologies, such as the use of ultrasonic waves and ozone treatment, are gaining popularity due to their effectiveness in removing microbial contaminants without leaving harmful residues. Ultrasonic waves generate cavitation bubbles that dislodge dirt and microbes from the surface, while ozone, a powerful oxidant, effectively kills bacteria and viruses. Effective washing is crucial, particularly for leafy greens, which have complex surfaces that can harbor pathogens. Proper drying after washing is equally important to prevent microbial growth during storage. Air drying, spin drying, or the use of absorbent materials are commonly employed to remove excess moisture from washed produce (Jayaraman & Gupta, 2020).

4.3 Packaging Innovations

Packaging is a critical component of postharvest handling that protects produce from physical damage, contamination, and environmental factors such as moisture loss and microbial invasion. Innovative packaging solutions not only enhance the visual appeal of produce but also play a significant role in extending shelf life and reducing post- harvest losses. Traditional packaging materials like wood, cardboard, and plastic are being supplemented with advanced materials designed to provide better protection and functionality. Active packaging, for instance, includes elements that interact with the internal environment of the package to control moisture, oxygen, and ethylene levels (Nielsen, 1997). This helps in delaying ripening and senescence, thereby extending the shelf life of the produce. Modified Atmosphere Packaging (MAP) and Controlled Atmosphere Packaging (CAP) are widely used technologies that alter the composition of gases within the packaging to slow down respiration rates and microbial growth. MAP involves the use of films with selective permeability to gases, allowing for the optimal balance of oxygen and carbon dioxide around the produce. CAP, on the other hand, involves actively controlling the gas composition during storage and transportation to maintain the quality of produce over extended periods. Biodegradable and compostable packaging materials are also gaining traction as environmentally friendly alternatives to conventional plastic packaging. These materials are made from renewable sources such as starch, cellulose, and polylactic acid (PLA), and they decompose naturally, reducing environmental impact (Rajeshkumar et al., 2021). These innovations not only address environmental concerns but also cater to consumer demand for sustainable packaging solutions. Nanotechnology is another frontier in packaging innovations, offering materials with enhanced barrier properties, antimicrobial activity, and sensors for monitoring the freshness of produce. Nano-packaging materials can effectively block the transmission of gases and moisture, thereby preserving the quality and extending the shelf life of perishable items.

5. STORAGE TECHNIQUES

Postharvest storage plays a critical role in extending the shelf life of horticultural crops, preserving their quality, and minimizing losses. Storage techniques like cold storage, controlled atmosphere storage, modified atmosphere packaging (MAP), and zero energy cool chambers are instrumental in maintaining the freshness and nutritional value of fruits and vegetables (Mullan & McDowell, 2011).

5.1 Cold Storage

Cold storage is a widely used technique for slowing down the metabolic processes of horticultural produce, thereby delaying senescence, reducing respiration rates, and minimizing the growth of spoilage organisms. By maintaining a low-temperature environment, cold storage helps in preserving the sensory and nutritional quality of fruits and vegetables.

Refrigeration Systems: Refrigeration systems form the backbone of cold storage facilities. These systems use mechanical refrigeration to maintain temperatures typically between 0°C and 10°C, depending on the type of produce. Modern refrigeration systems incorporate advanced technologies such as variable frequency drives (VFDs) and smart sensors to optimize energy consumption and maintain precise temperature control. For instance, apples and pears are stored at 0°C to 1°C, while tropical fruits like bananas require higher temperatures around 13°C to 14°C to prevent chilling injury (Couey, 1982). Energy efficiency is a major consideration in the design and operation of refrigeration systems. Innovations such as ammonia-based refrigeration and the use of natural refrigerants like carbon dioxide (CO_2) are gaining traction due to their lower environmental impact compared to traditional refrigerants.

***Controlled Atmosphere Storage*:** Controlled Atmosphere Storage (CAS) involves the manipulation of the atmospheric composition within the storage environment to extend the storage life of perishable produce. By reducing oxygen levels and increasing carbon dioxide levels, CAS slows down respiration and ethylene production, thereby delaying ripening and senescence (Sozzi et al., 1999).

5.2 Modified Atmosphere Packaging (MAP)

Modified Atmosphere Packaging (MAP) is a dynamic storage and packaging technique that alters the gas composition surrounding the produce within the package. By modifying the levels of oxygen, carbon dioxide, and nitrogen, MAP slows down respiration rates, delays ripening, and reduces microbial growth, thereby extending shelf life.

***Mechanism and Benefits*:** MAP works by using packaging films with selective permeability to gases. These films allow for the exchange of gases between the inside and outside of the package while maintaining the desired atmospheric composition. The optimal gas composition depends on the type of produce; typically, oxygen levels are reduced to 3-5%, and carbon dioxide levels are increased to 3-10% (Sandhya, 2010). The benefits of MAP include extended shelf life, reduced moisture loss, and enhanced product quality. MAP reduces the need for chemical preservatives and allows for the packaging of produce in convenient, retail-ready formats. This technique is particularly effective for fresh-cut fruits and vegetables, which are prone to rapid quality deterioration due to their high surface area and exposure to air.

***Applications in Horticulture*:** MAP is widely used for a variety of horticultural products, including leafy greens, berries, and fresh-cut fruits. For instance, strawberries packaged in MAP exhibit reduced respiration rates and maintain their firmness and color for an extended period. Similarly, fresh-cut lettuce benefits from reduced browning and microbial growth under MAP conditions. The integration of MAP with other storage technologies, such as refrigeration and CAS, further enhances its effectiveness. For example, the combination of MAP and refrigeration is commonly used for storing ready-to-eat salads, ensuring that they remain fresh and safe for consumption for up to two weeks (McCurdy et al., 2009).

5.3 Zero Energy Cool Chambers

Zero energy cool chambers (ZECCs) offer a sustainable and cost-effective solution for post-harvest storage, particularly in regions with limited access to electricity. ZECCs utilize the principle of evaporative cooling, where the evaporation of water from a porous surface (such as bricks or sand) absorbs heat, thereby lowering the temperature inside the chamber. ZECCs are typically constructed using locally available materials, such as bricks, sand, and thatch. The inner chamber, where the produce is stored, is surrounded by a layer of sand, which is kept moist. The evaporation of water from the sand cools the air inside the chamber, maintaining temperatures 10-15°C lower than the ambient temperature and relative humidity of around 90% (Song, 2014). This storage technique is particularly suitable for smallholder farmers and rural communities, where access to electricity is limited. ZECCs are effective for storing fruits like mangoes, bananas, and tomatoes, as well as leafy vegetables, extending their shelf life by several days to weeks, depending on the produce and climatic conditions. While ZECCs are not as effective as mechanical refrigeration in maintaining low temperatures, they offer a viable alternative for regions with high ambient temperatures and limited infrastructure. ZECCs are environmentally friendly, as they do not rely on electricity or refrigerants, reducing their carbon footprint.

6. POSTHARVEST TREATMENTS

Postharvest treatments play a vital role in extending the shelf life, enhancing the quality, and ensuring the safety of horticultural produce. These treatments include chemical, physical, and biological methods that help in managing decay, reducing physiological disorders, and preserving the nutritional and sensory attributes of fruits and vegetables (Scott & Ollis, 1995).

6.1 Chemical Treatments

Chemical treatments are widely used in postharvest management to control microbial decay, regulate ripening, and extend the storage life of horticultural crops. Two primary types of chemical treatments include the use of fungicides and growth regulators.

***Use of Fungicides and Growth Regulators*:** Fungicides are chemical compounds used to inhibit the growth of fungi that cause postharvest diseases such as anthracnose, graymold, and black spot. Commonly used fungicides include thiabendazole, imazalil, and fludioxonil, which are applied as dips, sprays, or fumigants. For example, thiabendazole is effective against Penicillium spp. in citrus fruits, reducing decay during storage and transportation (Schirra et al., 2008). However, the use of fungicides must be carefully managed to prevent the development of fungicide resistance and ensure compliance with maximum residue limits (MRLs) set by regulatory authorities. Growth regulators, such as ethylene inhibitors, are used to delay ripening and senescence in climacteric fruits like bananas, apples, and tomatoes. 1-Methylcyclopropene (1-MCP) is a widely used ethylene inhibitor that binds to ethylene receptors in the fruit, delaying ripening and extending shelf life. This treatment is particularly beneficial for long-distance transportation and storage, as it helps maintain fruit firmness, color, and overall quality.

6.2 Physical Treatments

Physical treatments are non-chemical methods used to control post- harvest decay, delay ripening, and enhance the storage life of produce. These treatments include heat treatments and irradiation.

***Heat Treatments*:** Heat treatments, such as hot water dipping, vapor heat, and hot air treatments, are employed to control post- harvest diseases and insect infestations, and to enhance fruit ripening and quality. Hot water dipping is commonly used for mangoes to control anthracnose and stem-end rot, while vapor heat treatment is effective for controlling fruit fly infestations in papayas and other tropical fruits (Yahia et al., 2011). Hot air treatment, on the other hand, is used for citrus fruits to reduce decay and improve peel quality. Heat treatments work by inactivating pathogens, enhancing the fruit's resistance to infections, and triggering beneficial physiological responses such as increased synthesis of heat shock proteins and enzymes involved in disease resistance. However, the application of heat treatments must be carefully controlled to avoid causing heat injury, which can lead to quality deterioration, such as skin browning and softening.

***Irradiation*:** Irradiation involves exposing produce to ionizing radiation, such as gamma rays, electron beams, or X-rays, to control microbial contamination, insect pests, and delay ripening. This treatment is effective in extending the shelf life of a wide range of horticultural products, including strawberries, onions, and potatoes (Ma et al., 2017). Irradiation works by damaging the DNA of microorganisms and pests, thereby preventing their reproduction and growth. The use of irradiation is approved by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) as a safe and effective post- harvest treatment. It does not leave any chemical residues and has minimal impact on the nutritional and sensory qualities of produce. However, consumer acceptance and regulatory restrictions remain challenges for the widespread adoption of irradiation.

6.3 Biological Treatments

Biological treatments utilize natural organisms or their metabolites to control post- harvest decay and enhance the storage life of produce. These treatments include the use of biocontrol agents and bio-preservatives.

***Biocontrol Agents and Bio-preservatives*:** Biocontrol agents are beneficial microorganisms, such as bacteria and fungi, which inhibit the growth of pathogens through mechanisms like competition, antibiosis, and induction of host resistance (Compant et al., 2005). Common biocontrol agents include *Bacillus subtilis, Pseudomonas fluorescens*, and *Trichoderma harzianum*, are providing effective control of postharvest diseases in various fruits and vegetables. For example, *Bacillus subtilis* produces antimicrobial compounds that inhibit the growth of fungal pathogens such as *Botrytis cinerea* and *Penicillium spp.* in strawberries and citrus fruits, respectively. The use of biocontrol agents is environmentally friendly and aligns with the growing demand for sustainable and organic post- harvest management practices. Bio-preservatives are natural compounds derived from microorganisms or plants that have antimicrobial properties. Examples include nisin, a bacteriocin produced by *Lactococcus lactis,* and plant extracts such as essential oils from oregano and thyme, which have been shown to inhibit the growth of pathogens like *Escherichia coli* and *Salmonella spp.* (Lacroix, 2007). These bio-preservatives are used as coatings, dips, or sprays to enhance the safety and shelf life of fresh produce.

7. ADVANCEMENTS IN PACKAGING TECHNOLOGIES

Packaging plays a pivotal role in the postharvest handling of horticultural produce, not only protecting it from physical damage but also significantly influencing its shelf life, quality, and safety. Advancements in packaging technologies have introduced innovative solutions like active packaging, intelligent packaging, and eco-friendly packaging. These innovations aim to enhance the functionality of packaging beyond mere containment and protection, addressing challenges such as ethylene management, microbial contamination, freshness monitoring, and environmental sustainability.

7.1 Active Packaging

Active packaging is designed to interact with the internal environment of the package, thereby enhancing the quality and extending the shelf life of the produce. This type of packaging can absorb or release substances like gases, moisture, or antimicrobial agents, depending on the specific needs of the produce (Labuza & Breene, 1989).

Ethylene Absorbers**:** Ethylene, a naturally occurring plant hormone, plays a critical role in the ripening and senescence of fruits and vegetables. In climacteric fruits such as bananas, apples, and tomatoes, excessive ethylene can accelerate ripening and lead to premature spoilage. Ethylene absorbers, a key component of active packaging, help mitigate this issue by removing or reducing ethylene levels within the package. These absorbers often contain substances like potassium permanganate, which oxidizes ethylene into harmless compounds (Kumar et al., 2024). For instance, ethylene-absorbing sachets are widely used in the packaging of bananas and avocados to delay ripening during transportation and storage.

Antimicrobial Packaging**:** Antimicrobial packaging incorporates substances that inhibit the growth of spoilage microorganisms, thereby enhancing the safety and shelf life of the produce. These substances can be integrated into the packaging material or applied as coatings. Common antimicrobial agents used include natural extracts like essential oils (e.g., oregano, thyme), organic acids (e.g., lactic acid), and bacteriocins like nisin. For example, packaging films infused with essential oils have been shown to effectively control microbial growth in fresh-cut fruits and vegetables, reducing spoilage and extending shelf life (Perumal et al., 2022).

7.2 Intelligent Packaging

Intelligent packaging goes beyond the traditional role of containment and protection, incorporating technologies that monitor and communicate the condition of the packaged produce. This helps in ensuring quality and safety by providing real-time information on parameters like temperature, humidity, and gas composition.

Sensors and Indicators**:** Sensors and indicators are integral components of intelligent packaging. These devices can detect changes in the internal environment of the package and provide visual or electronic feedback. For instance, time-temperature indicators (TTIs) monitor the cumulative exposure of the produce to temperature fluctuations, providing a visual cue (e.g., color change) when the produce has been exposed to temperatures outside the safe range (Corradini, 2018). This helps in identifying breaches in the cold chain and assessing the remaining shelf life of the product. Gas sensors, another type of intelligent packaging, are used to monitor the levels of gases like oxygen, carbon dioxide, and ethylene within the package. These sensors help in maintaining the optimal atmosphere for the stored produce, preventing spoilage, and ensuring quality. For example, oxygen sensors are used in modified atmosphere packaging (MAP) to ensure that the oxygen levels remain within the desired range, thereby slowing down respiration and microbial growth.

7.3 Eco-friendly Packaging Solutions

The growing awareness of environmental issues and consumer demand for sustainable products have driven significant advancements in eco-friendly packaging solutions. These packaging materials are designed to reduce environmental impact by being biodegradable, compostable, or made from renewable resources. Biodegradable packaging materials, such as polylactic acid (PLA), cellulose, and starch-based films, decompose naturally in the environment without leaving harmful residues (Kumari et al., 2022). For instance, PLA, derived from corn starch, is commonly used in the packaging of fruits and vegetables, offering similar performance to conventional plastics while being more sustainable. Compostable packaging materials go a step further by breaking down into organic matter that can enrich the soil. These materials meet specific standards set by organizations like ASTM and ISO, ensuring that they decompose under composting conditions without leaving toxic residues. Edible packaging, made from natural ingredients like proteins, polysaccharides, and lipids, offers an innovative solution for packaging fruits and vegetables. These films not only protect the produce but can also be consumed along with it, reducing packaging waste. For example, edible coatings made from alginate or chitosan are used to enhance the shelf life of fresh-cut fruits by reducing moisture loss and microbial growth (Yousuf et al., 2018). Recyclable packaging materials, such as polyethylene terephthalate (PET) and high-density polyethylene (HDPE), are widely used in the food industry. These materials can be reprocessed and used to manufacture new packaging or other products, thereby reducing the demand for virgin plastics and minimizing environmental impact.

8. TRANSPORTATION AND DISTRIBUTION

Transportation and distribution are critical components of the post- harvest system, ensuring that horticultural produce reaches consumers in optimal condition. The processes involved must address the perishability of produce, maintain quality and safety, and minimize losses throughout the supply chain. Key aspects of this process include cold chain logistics, the choice of transportation modes, and innovations in supply chain management.

8.1 Cold Chain Logistics

Cold chain logistics refers to the temperature-controlled supply chain essential for preserving the quality and extending the shelf life of perishable horticultural products (Aung & Chang, 2014). This system encompasses a series of coordinated actions, including pre-cooling, refrigerated transportation, and cold storage, designed to maintain the required temperature throughout the journey from farm to fork. Pre-cooling is the first critical step in the cold chain, where produce is rapidly cooled to remove field heat, reducing respiration rates and slowing down microbial growth. Methods such as forced-air cooling, hydro-cooling, and vacuum cooling are commonly used, depending on the type of produce. For instance, vacuum cooling is particularly effective for leafy greens, ensuring rapid and uniform temperature reduction. Refrigerated transportation, commonly known as reefer trucks, plays a crucial role in maintaining the cold chain during transit. These vehicles are equipped with refrigeration units that can be adjusted to the optimal temperature for different types of produce. Real-time temperature monitoring systems are often integrated into refrigerated transportation to ensure that temperature fluctuations are immediately detected and addressed (Gillespie et al., 2023). Cold storage facilities at distribution centers and retail outlets are the final link in the cold chain. These facilities use advanced refrigeration systems to maintain consistent temperature and humidity levels, ensuring the extended shelf life of the produce. Failure to maintain the cold chain can result in rapid quality deterioration, increased microbial activity, and significant post- harvest losses.

8.2 Transportation Modes and Their Impact

The choice of transportation mode significantly affects the quality, safety, and cost of transporting horticultural produce. Common transportation modes include road, rail, air, and sea, each with distinct advantages and challenges.

***Road Transportation*:** Road transport is the most commonly used mode for the distribution of fresh produce, particularly for short and medium distances. It offers flexibility in routing and scheduling, making it suitable for delivering fresh produce to urban and rural markets (Halder & Pati, 2011). However, the quality of road infrastructure and traffic congestion can impact the efficiency of road transportation. Properly equipped reefer trucks help mitigate these challenges by maintaining the cold chain.

***Rail Transportation*:** Rail transport is cost-effective and energy-efficient for long-distance transportation of large volumes of produce. It is particularly advantageous for bulk commodities like grains and potatoes. However, the limited availability of refrigerated railcars and the need for effective cold chain integration can pose challenges for perishable horticultural produce.

***Air Transportation*:** Air transport is the fastest mode, suitable for high-value, perishable produce like berries, flowers, and exotic fruits that require quick delivery to distant markets. Despite its speed, air transport is costly and has a high carbon footprint, making it less sustainable for large-scale distribution (Sgouridis et al., 2011). Ensuring temperature control during loading, flight, and unloading is critical to preserving the quality of air-transported produce.

Sea Transportation**:** Sea transport is the preferred mode for international trade of horticultural produce due to its cost-effectiveness for large volumes. Modern reefer containers used in sea transport are equipped with controlled atmosphere technology, which helps in maintaining the quality of produce like bananas, apples, and citrus fruits during long transits. The challenge lies in maintaining the integrity of the cold chain during loading and unloading at ports.

8.3 Innovations in Supply Chain Management

Advancements in supply chain management technologies have revolutionized the transportation and distribution of horticultural produce. These innovations enhance efficiency, reduce losses, and improve traceability across the supply chain.

Blockchain Technology**:** Blockchain provides a transparent and tamper-proof record of transactions and movements in the supply chain. It enables real-time tracking of produce from farm to fork, ensuring traceability and accountability (Sunny et al., 2020). Blockchain can help in identifying and isolating contaminated batches during food safety incidents, minimizing the impact on the entire supply chain.

Internet of Things (IoT)**:** IoT devices, such as smart sensors and GPS trackers, are increasingly being integrated into supply chains to monitor environmental conditions like temperature, humidity, and location in real-time. These devices provide valuable data that can be used to optimize routing, reduce transit times, and ensure compliance with cold chain requirements.

Artificial Intelligence (AI) and Machine Learning (ML)**:** AI and ML are being employed to analyze large datasets from IoT devices and other sources to predict demand, optimize inventory levels, and enhance decision-making in supply chain operations. For example, AI algorithms can predict potential delays or disruptions in transportation and recommend alternative routes to ensure timely delivery (Abduljabbar et al., 2019).

Collaborative Logistics Platforms**:** These platforms facilitate collaboration among different stakeholders in the supply chain, such as growers, distributors, and retailers. By sharing information and resources, collaborative logistics platforms help in reducing inefficiencies, optimizing logistics operations, and improving service levels.

9. QUALITY CONTROL AND SAFETY STANDARDS

Ensuring the quality and safety of horticultural produce post- harvest is crucial for meeting consumer expectations, complying with regulatory requirements, and maintaining market competitiveness. Quality control and safety standards involve rigorous assessment protocols, adherence to global standards and certifications, and the adoption of technological innovations for monitoring and maintaining produce quality.

9.1 Postharvest Quality Assessment

Postharvest quality assessment involves evaluating various attributes of horticultural produce to ensure it meets the desired standards for consumer acceptance and marketability. These attributes include physical characteristics (size, shape, color, texture), chemical composition (sugar content, acidity, moisture), and sensory qualities (flavor, aroma) (Barrett et al., 2010). Physical assessment often involves manual inspection, or the use of automated systems equipped with cameras and sensors to detect defects and classify produce based on size and color. Chemical assessments, such as measuring sugar content (using a refractometer) and acidity (using pH meters), help determine the ripeness and flavor profile of fruits. Sensory evaluation, conducted by trained panels, provides insights into consumer preferences and potential acceptance. Microbiological quality is another critical aspect, involving the detection of spoilage organisms and pathogens that could compromise food safety. Standard microbiological tests, such as total plate count and specific pathogen detection (e.g., E. coli, Salmonella), are commonly employed.

9.2 Global Standards and Certifications

Global standards and certifications ensure that postharvest practices align with internationally recognized safety, quality, and sustainability benchmarks. Key standards include:

- **Hazard Analysis and Critical Control Points (HACCP)**: This preventive system identifies critical points in the production process where potential hazards could be controlled to ensure food safety (Bryan & World Health Organization, 1992).
- **Global G.A.P. (Good Agricultural Practices)**: This certification covers the entire agricultural production process, including postharvest handling, to ensure safe and sustainable farming practices.
- **ISO 22000**: This international standard integrates food safety management systems and HACCP principles to ensure comprehensive food safety throughout the supply chain.

9.3 Technological Innovations in Quality Monitoring

Technological advancements have revolutionized quality monitoring in postharvest management, enabling more precise, efficient, and real-time assessments.

***Near-Infrared Spectroscopy (NIR)*:** NIR technology is a non-destructive method that assesses internal quality attributes like moisture, sugar content, and firmness without damaging the produce (Chandrasekaran et al., 2019). This technology is widely used in apples, grapes, and citrus fruits.

***Hyperspectral Imaging*:** This technique captures a wide spectrum of light to provide detailed information about the chemical composition and physical structure of produce. Hyperspectral imaging is effective in detecting defects, ripeness levels, and contamination.

***Smart Sensors*:** Integrated into packaging or storage environments, smart sensors monitor temperature, humidity, and gas composition (O_2, CO_2) in real-time. These sensors help in maintaining optimal storage conditions and alerting stakeholders to potential quality issues (Javaid et al., 2021).

10. EMERGING TECHNOLOGIES IN POSTHARVEST MANAGEMENT

Emerging technologies in postharvest management are transforming traditional practices by introducing innovative solutions that enhance efficiency, traceability, and sustainability.

10.1 Nanotechnology Applications

Nanotechnology offers significant potential in postharvest management by improving packaging materials, enhancing shelf life, and ensuring food safety. Nano-packaging materials, such as nanocomposites, provide superior barrier properties against oxygen, moisture, and ethylene, thus reducing spoilage and extending shelf life. Nano-sensors embedded in packaging can detect microbial contamination or changes in the product environment, providing real-time safety and quality alerts. Nanoscale coatings, such as those made from chitosan or silver nanoparticles, have antimicrobial properties that inhibit the growth of spoilage organisms and pathogens on fresh produce (Chaudhary et al., 2020). These coatings are particularly effective for fresh-cut fruits and vegetables, where microbial contamination is a major concern.

10.2 Use of Drones and AI in Postharvest Monitoring

Drones equipped with high-resolution cameras and sensors are increasingly used for monitoring post- harvest operations, such as inspecting storage facilities and transportation conditions. Drones can capture real-time data on environmental conditions, detect potential issues like temperature fluctuations or contamination, and provide actionable insights for corrective measures. Artificial Intelligence (AI) plays a crucial role in analyzing the vast amounts of data collected by drones and other IoT devices. AI algorithms can predict spoilage patterns, optimize storage conditions, and enhance decision-making in logistics and supply chain management (Pandey et al., 2023). Machine learning models can also help in grading and sorting produce by identifying defects and classifying fruits based on quality attributes.

10.3 Blockchain for Traceability and Transparency

Blockchain technology is revolutionizing traceability and transparency in the post- harvest supply chain by providing a decentralized, tamper-proof ledger of all transactions and movements. Each step in the supply chain, from harvesting to retail, is recorded on the blockchain, ensuring complete visibility and accountability. This technology enables stakeholders to trace the origin of produce, verify compliance with safety standards, and quickly identify and isolate contaminated batches in case of food safety incidents. Blockchain also empowers consumers by providing them with detailed information about the provenance, handling, and storage conditions of the produce they purchase (Leng et al., 2020).

11. CONCLUSION

The integration of advanced quality control, safety standards, and emerging technologies is transforming poatharvest management in horticulture. Emerging technologies, including nanotechnology, drones, AI, and blockchain, enhance efficiency, traceability, and sustainability. Nanotechnology improves packaging and shelf life, drones and AI optimize monitoring and logistics, while blockchain ensures transparency and accountability across the supply chain. Together, these advancements reduce post- harvest losses, improve operational efficiency, and ensure consumer satisfaction by delivering fresher, safer produce. This holistic approach supports global food security and sustainability, aligning with modern agricultural and consumer needs.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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