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Emerging technologies in postharvest handling of fruits: Reducing losses and enhancing quality

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Abstract
Post-harvest waste of fruits has rapidly become a serious global issue within the past few decades. This waste, which varies from 40% to 44%, is impacted by a number of biological, social and physical elements in the food and beverage and agriculture industries. From the early phases of crop production to product consumption, this kind of waste happens across the supply chain. This makes the food hazardous and unfit for ingestion. Reducing fruit waste would open the door to long-term solutions for issues related to food security, food safety, economic sustainability and detrimental environmental effects. To maintain the nutritional value and safety of fresh fruit, sophisticated postharvest physical and chemical treatments as well as biocontrol techniques have been used in recent decades in addition to traditional methods. When dealing with quality loss brought on by the length of time it takes to transport goods to far-off markets, the employment of these techniques after harvesting is helpful. By streamlining procedures like sorting, grading, packaging and microbial detection, artificial intelligence (AI) technologies like machine learning, computer vision and IoT integration are cutting down on food waste and increasing shelf life. AI's incorporation into supply chain optimization and demand forecasting is enhancing food traceability, avoiding interruptions and lessening the impact on the environment.

Keywords: Fruits, postharvest, quality, technologies, artificial intelligence

Introduction
Fresh fruit is a valuable source of antioxidants, vitamins and minerals. Because they are aware of these good's potential to prevent certain non-communicable diseases, consumers have become more inclined to eat them in recent decades. The evaluation of several visual attributes (size, shape, colour, gloss, firmness, texture and taste) and internal aspects (chemical, physical and microbiological) pertaining to nutritional characteristics, safety and sustainability are the main determinants of fruit quality (Chauhan *et al.*, 2017) [1]. Harvested goods are highly perishable and metabolically active. They experience quality losses as a result of ripening and senescence processes, which are frequently linked to the growth of spoilage microorganisms and other undesirable occurrences. These processes must be managed to maintain the product's quality and extend its shelf life while it is being stored (De Corato *et al.*, 202). Additionally, the presence of nutritional elements linked to these matrices and highwater activity can promote the proliferation of infections (Srisamran *et al.*, 2022) [2]. As a result, poor preservation techniques can negatively affect the economy at every stage of the supply chain, from growers to consumers, in addition to generating significant losses in nutritional and quality attributes. According to estimates from the Food and Agriculture Organization (FAO), postharvest spoiling accounts for 33% of all food produced for human use. In general, industrialized (developed) nations account for 44% of losses, while emerging nations account for 40% (Gustavsson *et al.*, 2022) [3]
Optimal postharvest handling can minimize microbial growth and contamination, slow down the biological processes brought on by senescence and maturation and reduce or inhibit the development of physiological disorders. This includes controlling storage time and temperature, relative humidity, chemical and/or physical treatments and packaging (*i.e.*, a modified atmosphere) (Mahajan *et al.*, 2014) [4]. For instance, the most significant and straightforward postharvest element that might postpone the product's deterioration is temperature (Brasil *et al.*, 2018) [5]. Each product typically has a suggested storage temperature and if the commodity is quickly cooled to its ideal postharvest storage temperature as soon as possible after harvest, optimal quality preservation can be attained (Kader, 2002)[6]. Fruit quality is assessed using conventional procedures (sensory evaluations and analytical methodologies), which are

labour-intensive, time-consuming and damaging. Furthermore, these methods are not appropriate for in-line use in commercial or industrial settings to provide customers with real-time information about the quality of the current product. Conversely, compared to traditional destructive methods, the new contactless and non-destructive technologies for fresh produce quality monitoring such as near-infrared spectroscopy, hyperspectral or multispectral imaging, image analysis, electronic noses, etc, offer many advantages (Chauhan, *et al.*, 2017) [1]. These new methods, which are primarily focused on the assessment of chemical or physical characteristics that correlate with specific quality qualities of agricultural goods, are typically employed for both internal and external quality evaluation (Bhargava & Bansal, 2021) [7].

In order to maintain fresh fruit quality and minimize postharvest losses and waste, this review article aims to provide a comprehensive collection of key applications of new postharvest physical and chemical emerging technologies.

Post-harvest loss stages

From harvest to final marketing and consumption, post-harvest losses happen at several points in the supply chain (Kiaya, 2014) [8].

- **Harvesting stage**
  Harvesting losses are often the result of inadequate harvest maturity selection, harsh handling and incorrect techniques (Yahia *et al.*, 2019) [9]. The risk of illness and infection is increased by mechanical injuries caused by incorrect tool use, excessive force or harvesting during bad weather (Ali *et al.*, 2019) [10].
- **Field Handling and packing stage**
  During field handling and packing, fresh food is more vulnerable to infection, bruising and moisture loss. The danger of bruising, compression injuries and microbiological contamination is increased by large containers, inadequate or defective packaging and unhygienic harvesting tools and containers. Intervals between harvesting and packaging, especially in hot weather, shorten marketability and storage life by increasing respiration and transpiration rates and causing rapid physiological degradation (Pokhrel, 2020) [11].
- **Transportation and storage stage**
  Microbial deterioration, disease development and physiological weight loss from transpiration account for the majority of post-harvest losses in storage. Storage life will be shortened and senescence accelerated if temperature, humidity and gas composition are not well controlled. In underdeveloped nations, the absence of cold storage facilities results in large losses, particularly for perishable goods like fruits and vegetables. Elik *et al.* (2019) [12] state that poor storage conditions are the main cause of postharvest losses in horticulture value chains.
- **Processing and marketing stage**
  The majority of the losses that happen throughout the production and marketing phase are caused by strict quality classification, cosmetic requirements and variations in market prices. Fruits that are nevertheless high in nutrients may be rated lower or thrown out due to their size, colour, form or other cosmetic flaws. Post-harvest losses are also caused by inadequate market infrastructure, processing and value-adding facilities and marketing delays.

Emerging technologies to reduce the post-harvest waste of fruits

Microwave

In order to achieve a quick and efficient temperature increase without a temperature gradient, microwaving was used in this situation as an alternative to traditional heating (Dar *et al.*, 2019) [13]. Fruits are temporarily treated using this method to control microbial development during the product's limited processing, avoiding quality losses while also ensuring the least amount of environmental impact and the absence of residues in the treated product (Usall *et al.*, 2016) [14]. High-power/short-time treatments were applied to minimally processed apples, showing encouraging microbiological outcomes (Colelli *et al.*, 2021) [15]. However, if the microwave therapy is applied for too long or with too much intensity, the temperature may rise too much and cause uneven heating, which could harm the fresh tissue (Vadivambal *et al.*, 2010) [16]. For fresh and lightly processed food, a successful microwave process on an industrial scale requires overcoming a number of obstacles.

Pulsed electric field

Pulsed electric field (PEF) technology has garnered a lot of attention lately because to its capacity to produce safe food with minimum heat generation by using µs to ms-pulses of a high electric field of high intensity (Vanga *et al.*, 2021) [17]. This method has been applied extensively to liquid, semi-solid and solid foods as well as fresh fruit, vegetable smoothies and juices. The strength of the electric fields, the duration of treatment and the frequency, polarity or form of the pulses are the PEF parameters that must be tuned in order to achieve microbiological and enzymatic inactivation in fresh items. In addition to having a longer shelf life and higher microbiological safety, PEF-treated items better preserved their fresh flavour, texture and functional qualities. However, the use of PEF is restricted to fresh-cut products since PEF-induced metabolic stress may have a detrimental effect on the final product's quality.

High hydrostatic pressure

The main applications of high hydrostatic pressure (HHP) technology are enzyme denaturation and microbial inactivation or reduction. However, high pressure that damages microbial cellular structures may have comparable effects on plant cells; therefore, a thorough investigation into treatment optimization in many new systems is necessary. Numerous findings demonstrate that HHP has a substantial impact on microbial burden, but because of the large range of product kinds, it also specifically and variably impacts the functionality of proteins, including enzymes and tissue structure (Rux *et al.*, 2020) [18]. Additionally, it was noted that nutraceutical substances were stimulated and accumulated.

Cold plasma

Cold plasma is a state-of-the-art method for controlling microbial growth in the whole and minimally processed fruit industry (Bagheri & Abbaszadeh, 2020) [19]. Its goal is to replace traditional sanitation treatments while maintaining the antioxidant and nutritional qualities of food products. Plasma therapy has been used to a number of fruit-based fresh-cut goods, with positive results in terms of quality indices and microbiological growth inhibition. The use of plasma-activated water (PAW) has also been extensively researched in recent years. This method is a useful substitute for the traditional approach of washing during fresh-cut processing for a number of goods since it enables the producer to prevent cell damage brought on by direct exposure to cold plasma. To date, cold plasma and PAW washing applications have been described for strawberries (Hozák, *et al.*, 2022) [20], kumquat fruit (Guo *et al.*, 2021) [21], blueberries (Hu *et al.*, 2021) [22], fresh cut apples (Perinban *et al.*, 2022) [23], pears (Zhang *et al.*, 2021) [24], cantaloupe melons (Zhou *et al.*, 2022) [25], kiwifruits (Zhao *et al.*, 2019) [26] and red currants (Limnaios *et al.*, 2021) [27]

Dipping and vacuum impregnation

Fresh-cut fruit's quality is greatly impacted by both physiological changes, such as enzymatic browning brought on by tissue damage and high respiration rates and physical factors, such as mechanical injuries and the removal of outer protective coverings, which result in faster weight loss, shriveling, colour and appearance loss and shorter shelf life (Siddiqui *et al.*, 2011) [28]. In order to preserve and enhance the quality and prolong the shelf life of these products, novel food processing technologies, such as dipping and vacuum impregnation techniques, are being researched and put into practice to sanitize, lessen enzymatic browning, improve the texture and fortify fresh-cut fruit with nutrients (vitamins, probiotics, minerals, organic acids, phenols, etc.) (Joshi *et al.*, 2020) [29]. Dipping treatments involve immersing the product with or without mechanical agitation and then draining the surplus solution. Because it promotes the solution's dispersion and covers the product's maximum surface area without causing damage or stress, this technique is frequently applied to whole, peeled, shredded and sliced commodities as well as more perishable goods (Martín-Diana *et al.*, 2007) [30]. The elimination of cellular exudates, which can negatively impact the postharvest quality of commodities is one of the main benefits of these dipping procedures.

The soaking time, frequency, solute composition, temperature and solution concentration are the variables of the dipping process that need to be optimized, depending on the food product. In their 2013 study, Giacalone and Chiabrando examined the effects of dipping apple cubes in solutions of citric acid and calcium salts (propionate or chloride). They found that the fruits treated with citric acid and calcium chloride had improved firmness, colour, sensory qualities and browning inhibition. When papaya slices were submerged in a water solution containing cinnamaldehyde, calcium chloride and their combinations, Albertini *et al.* (2016) [31] found that the combination treatment improved firmness maintenance and had an impact on flavour and taste. Other research has assessed the effects of dipping raspberry fruits in solutions of calcium chloride and pectin methyl-esterase (PME) on firmness and other quality attributes during refrigerated storage, demonstrating that the treatment increased the fruit's firmness and decreased its weight loss (Yan *et al.*, 2021) [32]. A contemporary strategy to enhance the quality and prolong the shelf life of fresh-cut fruit is the use of natural extracts (polyphenols, carotenoids, organic acids and bioactive peptides) as anti-browning agents (Hamdan *et al.*, 2022) [33].

Numerous natural compounds have been shown to reduce browning in fresh-cut fruits, including pomegranate peel (Turrini *et al.*, 2020) [34], mango peel (Jirasuteeruk & Theerakulkait, 2019) [35] and pineapple juice (Supapvanich *et al.*, 2017) [36]. Supapvanich *et al.* (2020) [37] tested the immersion of fresh-cut apple slices in coconut water and assessed various quality attributes (colour, enzymatic and antioxidant activity and visual quality) during storage. They found that coconut-liquid endosperms could prevent fresh-cut fruit from browning for up to nine days at 4 °C. The antioxidant activity of secondary plant metabolites, particularly the phenolic compounds, may be responsible for the inhibition of browning, according to Wessels *et al.* (2014) [38], who assessed the anti-browning effect of 36 plant extracts applied as dipping solutions on the enzymatic activity and colour parameters of fresh-cut apple slices.

Edible Active Packaging, Based on Natural Compounds

Edible polymers combined with natural antioxidants make up edible active packaging. By reducing a number of natural processes, such as gaseous exchange and the rate of respiration and transpiration, edible coatings have demonstrated efficacy as a principal packaging material in postponing ripening, maintaining nutritional qualities and preventing quality loss (Pandey *et al.*, 2022) [39]. It has recently been noted that adding active natural ingredients with antimicrobial and/or antioxidant qualities can greatly increase the effectiveness of edible coatings. These packaging items, referred to as "active," are made to interact with food by releasing biologically active ingredients.

Even in the absence of cold storage, the incorporation of active chemicals into biopolymer matrices improves the food product's oxidation stability and prevents the growth of food-borne pathogens, giving it additional safety attributes (Rangaraj *et al.*, 2021) [40]. Sweet cherries's shelf life has been shown to be extended by an edible covering made of alginate and chitosan enhanced with olive leaf extract. Additionally, there was a delay in the ripening process and a notable retention of phenolic and antioxidant components when compared to the uncoated samples (Zam, 2019) [41]. According to Robles-Sánchezetal *et al.* (2013) [42], fresh-cut mangoes were able to maintain a number of quality characteristics, including colour, phenolic content and antioxidant activity, when an alginate coating was combined with citric and acetic acid. Nevertheless, *β-carotene* and flavonoids could not be preserved.

Additionally, during the storage period of fresh-cut apples, an edible covering containing 1% chitosan and 5% ascorbic acid prevented browning, maintained flesh firmness, postponed microbiological growth and preserved phenolic components (Özdemir, K.S, Gökmen, 2019) [43]. According to Carvalho *et al.* (2016) [44], a 2% chitosan-based coating enhanced with 500 mg L−1 antimicrobial *trans-cinnamaldehyde* maintained the fresh-cut cantaloupe melons' firmness, lightness and total vitamin C and carotenoids content while they were stored at 4 °C. It has been observed that adding lemon essential oil to a chitosan edible coating lowers strawberry respiration rates and increases chitosan's antifungal activity against *Botrytis cinerea* (Perdones *et al.*, 2012) [45]. Additionally, the chitosan coating prevented the growth of mold and kept the product's textural qualities, especially hardness, without materially altering the fruit's acceptability to consumers during the storage time. In order to preserve raspberry fruits, Vieira *et al.* (2022) [46] applied chitosan-based active film pads enhanced by ethanolic extracts of rosemary and green tea as natural antifungal agents to the bottom of commercial trays. This environmentally friendly packaging effectively reduced the incidence of raspberry fruit fungus, maintained overall quality while in storage and increased fruit shelf life by up to 14 days.

Strategies of biocontrol

These complex microbial ecosystems encompass the diversity of naturally associated bacteria, yeasts and filamentous fungi (molds) (Kłape´ *et al.*, 2022) [47]. This microbial variety can play a highly varied role at harvest, influencing the postharvest good's quality and safety (Vermote *et al*., 2022) [48]. In relation to the food matrices of interest, this microbiota may be linked to undesirable microorganism pathogens, toxin makers, bacteria with antibiotic resistance genes and/or possible spoiling activity (Zhang, *et al*., 2020) [49]. Additionally, postharvest procedures, workers and surroundings may give rise to these unwanted microbes (De Simone *et al*., 2020) [50]. Biocontrol, which uses specific microorganisms as control agents, is thought to be one of the more environmentally friendly postharvest methods for extending fruit shelf life (Capozzi *et al*., 2021) [51]. Applying certain microbes that can prevent the growth of unwanted germs is the foundation of bio-protection. The concept of using the fruit's microbiome as a target provides a unique viewpoint for comprehending the factors involved in biocontrol solutions, including the growing interest in products designed for preharvest applications that also show potential for postharvest biological control (Sellitto *et al*., 2021)[52].

High-pressure processing technology

Among non-thermal food preservation techniques used in large-scale applications, this approach is thought to be the most advanced new food processing technology. The supercritical fluid and homogenizers employed in the technology determine the pressure levels, which vary from tens to hundreds of MPa. Therefore, the primary purpose of this technique is to inactivate the bacteria and it has several other benefits in the field of food structural engineering. The packed food is put within an outside container throughout this technology's processing processes and it is automatically inserted inside the high-pressure vessel before its valves are sealed. Water is typically the medium used to transfer pressure and it is forced into the appropriate vessel from one or both sides. No further electrical input is needed to sustain the pressure for the remainder of the stay once the pumping mechanism has reached its targeted maximal pressure. The isostatic idea of pressure transmission can guarantee that every molecule in the high-pressure vessel is exposed to the same level of pressure at the same processing time, unlike other thermal processes where temperature gradients exist. This technology is frequently employed in fruit juice production because of its benefits, which include preserving the treated food commodities' natural sensory and nutritional profile (Knorr *et al*.,1941) [53].

Cold plasma technology

Today, cold plasma technology is becoming more and more common in the food sector because of its effectiveness in completely inactivating dangerous microorganisms, such as those that produce spores and other hazardous entities present in food. This process damages the biological cell's DNA by inactivating microorganisms mainly by oxidative stress or physical lysis (Tropea, 2022) [54]. Since cold plasma technology can improve printability, adhesive qualities and degree of polymerization, it has been demonstrated to have great potential in food packaging. Cold plasma technology has been used in the food preservation sector to preserve apples and other fruits; as a result, the technology works well at room temperature and lessens the impact of temperature increases on nutritional and sensory qualities (Tropea, 2022).

Ultrasound technology

A promising technique for preserving fruit-based food products is ultrasound technology. Its benefits include limiting flavour loss, conserving energy, improving consistency, increasing productivity, lowering chemical and physical dangers, improving produce quality and being eco-friendly (Chemat *et al*., 2011) [55]. Ultrasonic power, a form of vibrational energy, powers ultrasound technologies. During the treatment procedure, a transducer generates this energy by transforming electrical energy into sonic energy (Lauteri *et al*., 2023) [56]. In food processing processes, the ultrasonic energy can be maximized through direct exposure or the use of devices such an ultrasonic water bath or sonotrode. More fruit-based food preservation has been demonstrated by the use of ultrasonic energy during the processes of filtration, freezing and crystallization, thawing, brining, drying, foaming and de-foaming, extraction and degassing. Applying ultrasonic energy at the same stage is demonstrated to induce the fundamental principle that occurred during food preservation through the aforementioned technologies (Bhargava *et al*., 2021) [7].

AI-driven innovations in post-harvest technologies

- **AI for sorting and grading**
  In post-harvest operations, AI technologies more especially, machine learning (ML) and computer vision (CV) are streamlining the sorting and grading procedures, especially for fruits (Opara *et al*., 2024) [57]. These developments lower labour expenses and human error while increasing sorting job's speed, accuracy and efficiency. By offering more accurate evaluations of food attributes, AI integration can improve food quality, decrease waste and boost supply chain efficiency. Large picture and sensory data databases are used to train machine learning (ML) algorithms to recognize and categorize different food attributes (Saha & Manickavasagan, 2021) [58]. Food good's size and form can be measured by AI systems to see if they fit certain requirements for distribution or packaging. AI can evaluate a fruit's ripeness by examining its colour, texture and other characteristics. AI systems, for instance, can identify colour changes in bananas that signify different stages of ripeness, making it easier to decide when to harvest or sell the fruit. Using high-resolution images, AI models may also detect physical flaws like bruising, cracks, mildew, or discolouration. As a result, there is less waste, better operational efficiency and higher customer satisfaction.
- **AI in quality control and inspection**
  AI technologies are revolutionizing the food sector by improving real-time food quality monitoring by automating the identification of pollutants, pathogens and spoilage. AI systems can offer more precise, fast and scalable solutions for guaranteeing food quality, increasing shelf life and reducing waste by combining machine learning models, sensors and data analytics. Using patterns in food photos and sensor data, such colour shifts, AI models can identify rotting (Padhiary *et al*., 2023) [59], texture degradation and microbial growth on food surfaces. Additionally, obvious indicators of spoiling, including mold development or bruising, can be found via image analysis. AI models are able to identify physical pollutants like plastic, glass, metal or dirt as well as foreign items in food goods. By examining microbial activity, genetic markers or alterations in ambient conditions, AI can also detect foodborne diseases such as *Salmonella*, *E. coli* or *Listeria* (Kumar, *et al*., 2024) [60], DNA-based detection can be used to match these sequences against a database of known pathogens, providing faster and more accurate results. Without the need for human inspection, automated inspection systems

are able to detect flaws, contamination and spoiling in real time.

- **Predictive analytics for shelf-life and storage**
By anticipating and controlling post-harvest storage and transportation, AI-powered predictive analytics is extending food product's shelf lives. AI algorithms can more accurately predict shelf life by utilizing information from food types, ambient factors and past trends (Pandey *et al.*, 2023) [61]. AI systems can optimize storage settings to guarantee that food items are kept in optimal conditions, eliminating waste, preventing spoiling and increasing product longevity. By examining sensor data pertaining to temperature, humidity and gas composition, AI can optimize storage settings in real-time. Additionally, AI can learn the best storage parameters at every stage of the product's life cycle and dynamically modify them over time. This makes it possible to perform preventative maintenance before temperature changes compromise the quality of food that has been stored.
- **Enzyme and microbial control**
In postharvest food preservation, enzyme and microbial management are essential because they impact food safety, quality and shelf life. Polyphenol oxidase (PPO), peroxidase (POD), lipase, protease and pectinase are examples of enzymes that AI can track in food to reduce their negative effects on food quality (Nardella *et al.*, 2023) [62]. By forecasting the best circumstances and times for treatments that deactivate enzymes, AI can help improve postharvest enzyme inactivation, guaranteeing food quality is maintained without overprocessing. Using sensor technologies like biosensors, which continuously monitor food goods throughout storage and transportation, AI can also identify microbial contamination in real-time (Padhiary *et al.*, 2024) [63] (Zhang *et al.*, 2024) [64]. Proactive control techniques are made possible by predictive microbial growth models, which can detect possible spoiling concerns before they materialize. Enzymatic activity and microbiological contamination have been demonstrated to be effectively controlled by cold plasma technology, an innovative non-thermal technology (Nwabor *et al.*, 2022) [65]. AI and cold plasma together have a minor impact on sensory qualities as flavour, texture and nutritional value.

Challenges in implementation

1. **High initial investment costs**
It costs a lot to set up packing facilities, cold storage, refrigerated shipping and controlled environment systems. Small farmers may find it challenging to absorb these high expenses, especially in the absence of easily accessible loans or subsidies.
2. **Limited access to skilled human resources**
Staff with training in cold chain operations, grading, harvesting, storage management and quality control are necessary for effective post-harvest management. Lack of qualified personnel and technical expertise restricts the effective use of current infrastructure in many places.
3. **Limitations smallholder farmers**
Institutional loans, established markets and contemporary postharvest services are frequently inaccessible to small farmers. Their limited productivity, dispersed landholdings and weak bargaining power make it even harder for them to take part in value-added supply chains.
4. **Regulatory and certification barriers**
It can be expensive and difficult to comply with certification criteria, food safety regulations, grading procedures and quality standards. Small manufacturers and processors frequently find it difficult to comply, which restricts their access to profitable domestic and international markets.

Future prospects and research gaps

It is becoming more widely acknowledged that lowering post-harvest losses in horticulture crops is a smart way to boost sustainability, farmer income and food security. Despite the significant improvements in postharvest technologies and management techniques, there are still a number of opportunities and important research gaps that need to be filled in order to have a significant long-term impact.

- **Development of low-cost and scalable technologies**
Future studies should concentrate on creating affordable, scalable and energy-efficient post-harvest solutions for smallholder farmers. Innovations that need to be optimized and validated at the field level in a variety of agroclimatic settings include solar-powered cold storage, improved zero-energy cool chambers and reasonably priced packaging materials.
- **Crop-specific post-harvest management protocols**
Because fruits differ greatly in their physiological behaviour and storage needs, postharvest handling and storage procedures must be tailored for each crop and geographical area. Standardization of maturity indicators, ideal storage conditions and methods for extending the shelf life of native and underutilized horticultural crops should be the focus of future research.
- **Integration of digital and smart technologies**
- Despite their great promise, digital technologies like artificial intelligence (AI), Internet of Things (IoT)-based monitoring and decision-support systems are still rarely used. To evaluate their cost-benefit ratios, data interoperability, farmer and handler usability and integration into current value chains, more investigation is required.
- **Eco-friendly and chemical-free post-harvest treatments**
The necessity for research on biocontrol agents, plant-based extracts, edible coatings and physical treatments (such as heat, UV and irradiation) is highlighted by the growing consumer demand for safe and residue-free produce. It is necessary to do long-term research on these alternative's safety, effectiveness and regulatory acceptability.
- **Advanced packaging materials and sustainability**
Intelligent, recyclable and biodegradable packaging methods that can preserve quality while reducing their detrimental effects on the environment require more investigation. Nanotechnology-based packaging's life cycle analyses and commercialization tactics should also be taken into account.
- **Quantification of post-harvest loss and data gaps**
There are few trustworthy and regular statistics on post-harvest losses by crop and stage, especially in poor nations. Evidence-based policies and focused actions require better techniques for loss assessment and real-time monitoring.

Conclusion

By implementing effective postharvest processing technology, fruit losses were reduced and food availability was improved, which could lessen consumer scarcity of agricultural products.

Strong communication and idea sharing between farmers, postharvest engineers, food technologists and fruit market specialists have been necessary for the effective elimination of postharvest losses. This is because advanced research and the application of new scientific approaches can reduce postharvest losses and extend shelf life. The right and scientific processing is necessary to maintain the consumable commodities physical look, flavour, market value and other qualities. In order to overcome the scarcity of fruits everywhere in the world, there is an increasing need to minimize fruit losses globally. By using intense and contemporary technology, this would help to raise the *per capita* availability of fruits because a decrease in losses would naturally increase the availability of products without requiring additional resources to increase output and productivity. This gives a summary of how advanced postharvest tools (such as active packaging, dipping, vacuum impregnation, pulsed electric field, high hydrostatic pressure and cold plasma) and biocontrol methods preserve the high nutritional value and enhance product safety after harvesting, thereby prolonging their shelf-life. Furthermore, combining other methods with those that have been documented may improve the product's quality and safety. Consequently, in order to meet consumer demands, the fruit industry has innovated by adopting these technologies. However, to confirm the true applicability, cost analysis is required. Food quality, safety, efficiency and sustainability are all being enhanced by AI-driven technologies in the post-harvest industry. Conventional post-harvest handling techniques frequently have trouble controlling intricate supply lines, minimizing losses and maintaining food quality. Food waste is decreased and shelf life is increased by using AI technologies, such as machine learning, computer vision, predictive analytics and IoT integration, to automate sorting, grading, packaging, quality control and microbiological detection. Therefore, it is necessary to have portable tools that can be used in the field or on industrial lines. New technologies that increase shelf life and make it possible to continuously check product quality at every stage of the supply chain are the subject of ongoing research.

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