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Emerging postharvest technologies to enhance the shelf-life of horticultural crops: An overview

Rachita Paul, Dipa Sanyal, Aritra Malik and Tanmoy Sarkar

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Rachita Paul
Department of Agriculture,
Swami Vivekananda
University, West Bengal, India

Dipa Sanyal
Department of Agriculture,
Swami Vivekananda
University, West Bengal, India

Aritra Malik
Department of Agriculture,
Swami Vivekananda
University, West Bengal, India

Tanmoy Sarkar
Department of Agriculture,
Swami Vivekananda
University, West Bengal, India

Corresponding Author:
Tanmoy Sarkar
Department of Agriculture,
Swami Vivekananda
University, West Bengal, India

Abstract

The postharvest period often sees a decline in the quality and shelf life of fresh produce due to insufficient postharvest facilities. To preserve the nutritive value and safety of fresh produce, modern postharvest treatments, including active packaging, dipping, vacuum impregnation, conventional heating, pulsed electric field, high hydrostatic pressure, and cold plasma, as well as biocontrol methods, have been implemented in recent decades. Addressing product quality loss brought on the lengthy transportation of goods to far-off markets, the implementation of these approaches after harvesting is helpful. Emerging technologies such as image analysis, electronic noses, and near-infrared spectroscopy exemplify non-destructive, contactless methods for quality monitoring. These approaches offer numerous advantages over traditional, destructive procedures and play a crucial role in preserving quality, reducing losses, and minimizing waste in fresh produce. This review article consolidates distinctive studies on advancements in postharvest technology to address these concerns. The efficiency and benefits of a few non-destructive, contactless technologies for gauging the quality of fruits and vegetables will also be described, and they will be contrasted with more conventional approaches.

Keywords: Active packaging, hydrostatic pressure, cold plasma, innovative postharvest technologies

Introduction

Postharvest technologies (PHT) encompass an interdisciplinary field of science and techniques applied to agricultural commodities after harvest. The primary objectives include preservation, conservation, quality control/enhancement, processing, packaging, storage, distribution, marketing, and utilization to fulfill the food and nutritional needs of consumers. This involves all treatments or processes from the moment of harvesting until the food product reaches the end consumer. The significance of postharvest technologies lies in their capacity to address the food requirements of a growing population by reducing avoidable losses, transforming low-grade raw commodities into more nutritional food items through proper processing and fortification, and converting a portion of food material intended for cattle feed into nutritive animal feed by processing and fortifying low-grade food, organic waste, and by-products.

Abundant quantities of vitamins, minerals, and antioxidants are present in fresh fruits and vegetables. Growing consumer awareness regarding these products' capacity to prevent various non-communicable diseases has led to an increased inclination toward their consumption. Traceability and the enhancement of safety, encompassing chemical, toxicological, and microbiological aspects, are vital considerations for all participants in the supply chain-from the farm to the consumer (Mahajan *et al.* 2014) [1]. The amalgamation of diverse physical and chemical attributes, including appearance, texture, flavor, and nutritional content, collectively influencing customer acceptability, is commonly referred to as food quality. Size, shape, color, gloss, hardness, texture, and taste are among the numerous exterior and interior characteristics utilized to assess the quality of fruits and vegetables.

Harvested products, being highly perishable and metabolically active, undergo quality deterioration due to ripening and senescence processes often associated with the proliferation of spoilage bacteria and other undesirable occurrences. To preserve the quality and extend shelf life during storage, it is essential to regulate these processes (Barth *et al.* 2009; De Corato *et al.* 2020) [3, 4].

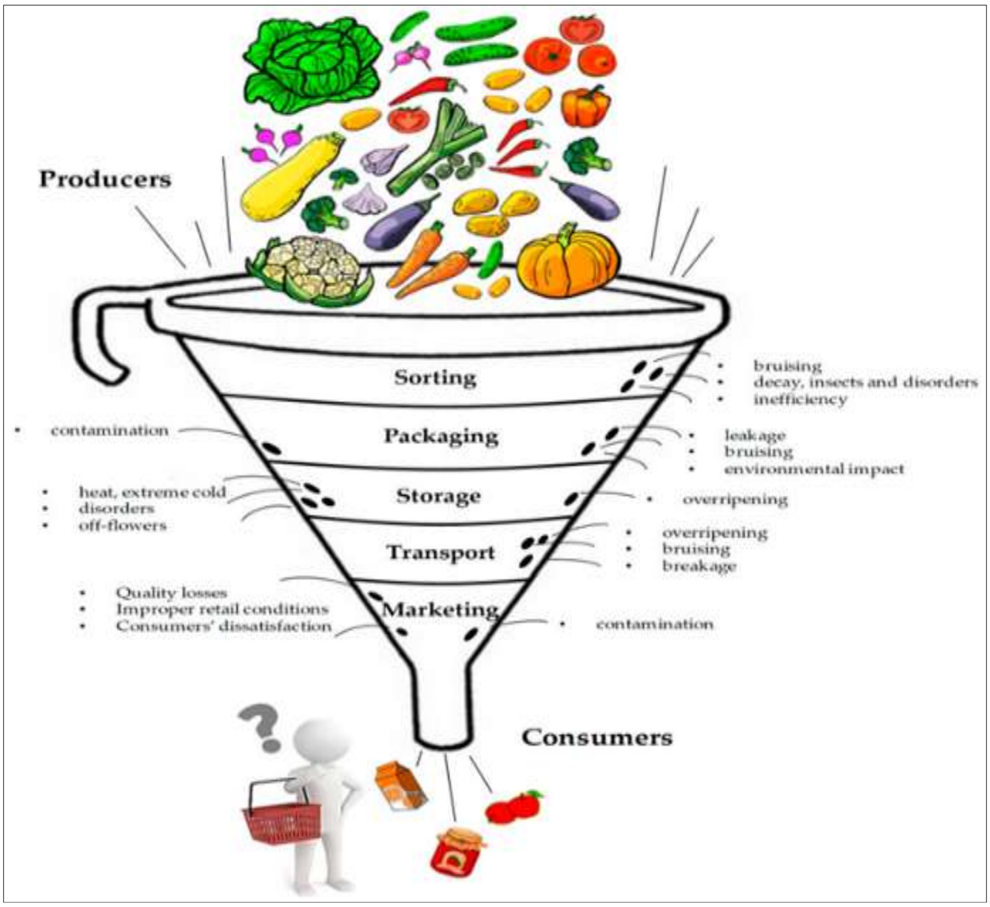


Fig 1: Causes of postharvest losses along the supply chain. (Bourne, M. Cornell University: Ithaca, NY, USA, 1977.)

Additionally, the growth of pathogens can be facilitated by high water activity and the availability of nutritional components within these matrices (Berger *et al*., 2010; Srisamran *et al*. 2022) [5, 6]. The superior sensory and nutritional attributes of fruits and vegetables hold significant commercial value. Consequently, inadequate preservation techniques can negatively impact the entire supply chain, affecting growers and consumers alike, leading to substantial losses in nutritional and qualitative features. According to the Food and Agriculture Organization (FAO), an estimated 33% of the total food produced for human consumption is lost due to postharvest spoilage, with 44% occurring in industrialized (Developed) countries and 40% in developing countries (Gustavsson *et al*. 2022) [7].

Fruits and vegetables, ranked as the food group with the second-highest level of losses and waste (Approximately 22%), come second only to roots, tubers, and oil-bearing crops across all stages of the food supply chain, as illustrated in Figure 2, according to a recent report from the FAO. This high percentage can be attributed to the inherent perishability of fruits and vegetables. To uphold the nutritional content and safety of fresh produce, contemporary post-harvest technologies such as physical and chemical treatments (Including active packaging, dipping, vacuum impregnation, conventional heating, pulsed electric field, high hydrostatic pressure, and cold plasma) can be employed. The detailed processing mechanisms of these innovative technologies are elucidated step by step below

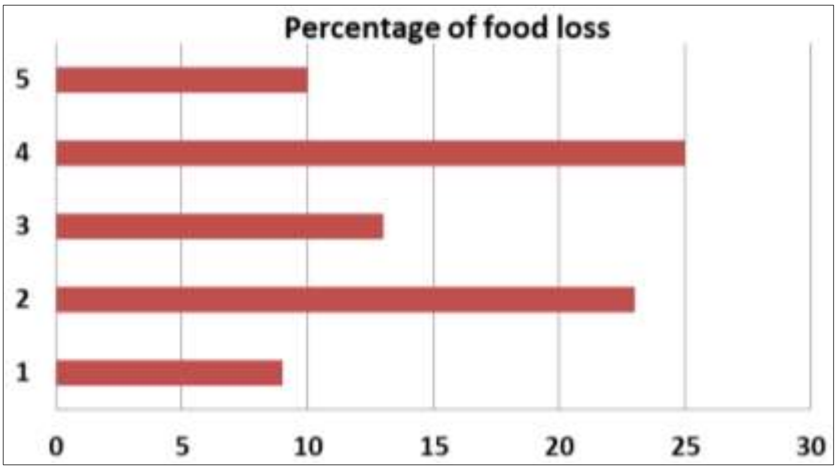
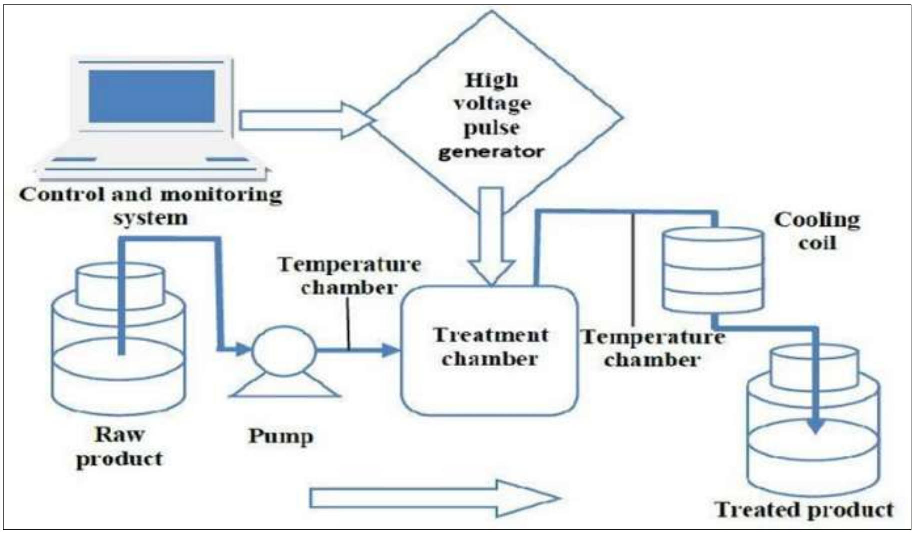


Fig 2: Food losses and waste along the supply chain (Percentage for each food group)

Postharvest Strategies to Extend the Shelf-Life of Fruit and Vegetables

Pulsed electric field

Due to its potential to produce safe food with little heat generation through the use of s to ms-pulses of a high electric field of high intensity, pulsed electric field (PEF) technology has recently gained the most attention (Vanga *et al*. 2021) [8]. This method has been applied to a wide variety of liquid, semi-solid, and solid foods, including juices, smoothies, and fresh fruit and vegetable products. The electric field intensity, treatment time, and frequency, polarity, or pulse shape are the PEF characteristics that must be tuned to achieve microbiological and enzymatic inactivation in fresh items.



High hydrostatic pressure

The primary applications of high hydrostatic pressure (HHP) technology involve enzyme denaturation and the reduction or inactivation of microbes. Nevertheless, the impact of elevated pressure on plant cells mirrors its effects on microbial cellular structures, necessitating thorough exploration for optimizing treatments across diverse fresh systems. Numerous investigations suggest that HHP significantly affects microbial load. However, owing to the extensive range of product types, it also manifests specific and diverse impacts on protein functionality, encompassing enzymes and tissue structure (Rux *et al*. 2020) [9]. Furthermore, there are observations of the activation and accumulation of nutraceutical components. The use of HHP has shown beneficial effects on various minimally processed horticultural products (Ramos-Parra *et al*. 2019; Hu *et al*. 2020; Kundukulangara *et al*. 2021) [10, 11, 12], whole produce (Paciulli *et al*. 2019; Paciulli *et al*. 2021; Hu *et al*. 2021; Pokhrel *et al*. 2022) [13, 15, 11, 17], and juice, indicating its effectiveness in enhancing diverse aspects of food safety.

Cold plasma

Cold plasma has become a widely adopted innovative technology in the management of microbial growth within the entire fruit and vegetable industry, both whole and minimally processed (Ahmadnia *et al*. 2021) [18]. The objective is to replace conventional sanitation methods while preserving the nutritional and antioxidant attributes of food products. Several academic studies have demonstrated the effectiveness of non-thermal plasma on various horticultural products (Table 1). In terms of quality standards and the prevention of microbial growth, plasma treatment has been successfully applied to numerous fresh-cut fruit-based products. The utilization of plasma-activated water (PAW) has gained increasing attention in recent years. Employing this approach allows producers to prevent cell deterioration caused by direct exposure to cold plasma, offering an excellent alternative to the traditional washing solution during the fresh-cut processing of various products. Up to now, applications of cold plasma and PAW washing have been reported for strawberries, kumquat fruit, green leafy vegetables (Ahmadnia *et al*. 2021; Rana *et al*., 2020; Giannoglou *et al*. 2020; Silveti *et al*. 2021) [18, 19, 20, 21], blueberries, fresh-cut apples, pears (Zhou *et al*., 2020) [27], cantaloupe melons, mushrooms, tomatoes, kiwifruits, and red currants.

Dipping and vacuume impregnation

To sanitize, mitigate enzymatic browning, enhance texture, and fortify fresh-cut fruits and vegetables with nutrients (Such as vitamins, probiotics, minerals, organic acids, phenols, etc.), researchers are exploring and adopting innovative food processing technologies, including dipping and vacuum impregnation techniques. One of the primary advantages of these dipping procedures is the elimination of cellular exudates, which can adversely affect the postharvest quality of commodities. The dipping process involves optimizing variables such as soaking time, frequency, solute composition, temperature, and solution concentration based on the specific food product. Calcium (Ca) salts have been investigated in several studies as dipping treatments to extend the shelf life of items. Ca enrichment offers various benefits, including preventing browning caused by oxidation and the development of off flavors in fresh-cut foods. It also enhances texture, acceptability, and storability.

A method known as food vacuum impregnation (VI) (see Figure 3) allows manufacturers to intricately introduce, dissolve, or suspend materials into the void fraction (i.e., pores) of a food matrix. The VI process involves two main steps: (1) reducing the pressure in the system (under vacuum) until mechanical equilibrium is reached, eliminating native gases and liquids, and expanding the product pores under pressure gradients; (2) restoring atmospheric pressure (during the relaxation period), filling the pores with the external solution as tissues relax, and reaching a new equilibrium. The vacuum impregnation process induces hydrodynamic mechanisms and deformation-relaxation phenomena, resulting in the flow of external solutions.

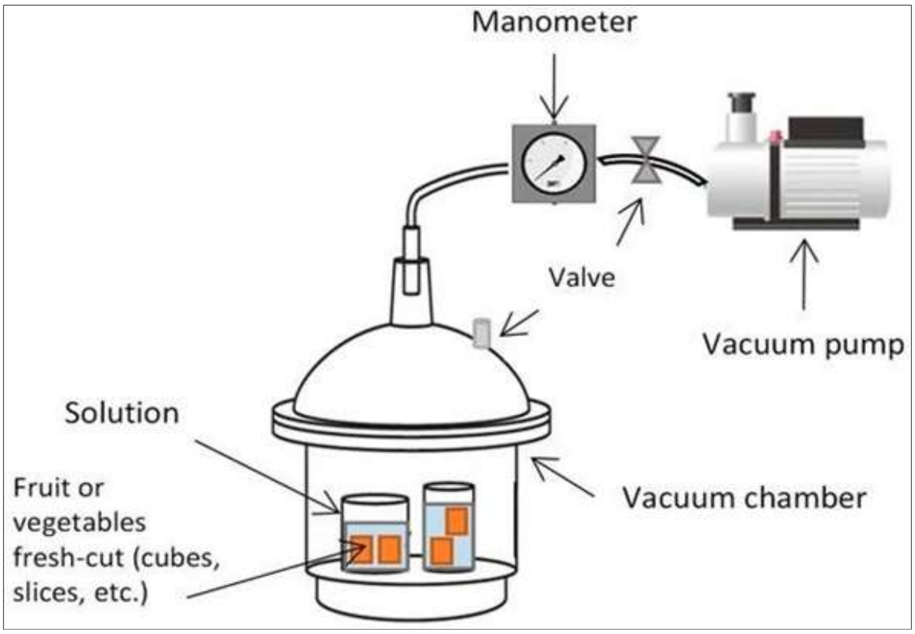


Fig 3: Schematic representation of the vacuum impregnation device, the arrows point at each system element

Active packaging

Active packaging is defined as packaging in which subsidiary constituents have been deliberately included in or on either the packaging material or the package headspace to enhance the performance of the package system.

Active packaging System	Mechanism	Food application
Oxygen absorber	Iron-based, metal/acid, metal (e.g., platinum) catalyst, ascorbate/metallic salts, enzyme-based and nylon MXD6	Bread, cakes, cooked rice, biscuits, pizza, pasta, cheese, cured meats and fish, coffee, snack foods, dried foods and beverages
Carbon dioxide absorbers/ emitters	Iron oxide/ calcium hydroxide, ferrous carbonate//Activated charcoal and ascorbate/sodium bicarbonate	Coffee, fresh meats and fish, nuts and other snack foods and sponge cakes
Ethylene absorbers	Potassium permanganate, activated carbon and activated clays/zeolites	Fruits and vegetables
AM packaging	Organic acids, silver zeolite, spice and herb extracts, BHA/BHT antioxidants,	Cereals, meats, fish, bread, cheese, snack foods, fruits and vegetables
	vitamin E antioxidant, chlorine dioxide and sulfur dioxide	
Ethanol emitters	Encapsulated ethanol	Pizza crusts, cakes, bread, biscuits, fish and bakery products
Moisture absorbers	Poly(vinyl acetate) blanket, activated clays and minerals and silica gel	Fish, meats, poultry, snack foods, cereals, dried foods, sandwiches, fruits and vegetables
Flavor/odor adsorbers	Cellulose triacetate, acetylated paper, citric acid, ferrous salt/ascorbate and activated carbon/clays/zeolites	Fruit juices, fried snack foods, fish, cereals, poultry, dairy products and fruits
Self-heating and self-cooling	Quicklime/water, ammonium nitrate/water and calcium chloride/water	Ready meals and beverages
Changing gas permeability	Side chain crystallizable polymers	Fruits and vegetables

Kerry, J. and Butler, P. (Eds), John Wiley & Sons, Ltd, New York, pp. 1-18, 2008.

Conclusion

This article provides an overview of the impact of state-of-the-art postharvest techniques (Including active packaging, dipping, vacuum impregnation, pulsed electric field, high hydrostatic pressure, and cold plasma) and biocontrol methods on preserving the high nutritional value and safety of fresh produce post-harvest. Both physical methods (Such as microwaving, pulsed electric fields, high hydrostatic pressure, and cold plasma) and a biocontrol approach have proven successful in enhancing product safety and extending shelf life. Manufacturers aiming to preserve freshness and enhance the nutritional content of fresh fruits and vegetables are encouraged to utilize technologies like dipping, vacuum impregnation, and edible active packaging. The incorporation of additional approaches, beyond those mentioned, can positively impact the reliability and overall quality of these products. The adoption of these technologies represents an innovation in the fruit and vegetable industry to meet consumer demand. However, a cost analysis is essential to confirm their practical applicability. Portable tools suitable for field or industrial use are crucial for the implementation of these techniques. Ongoing research is focusing on exploring advanced technologies that not only extend shelf life but also enable continuous quality monitoring throughout the entire supply chain.

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