REVIEW ARTICLE

Innovations and strategies in post-harvest handling and value addition of horticultural produce

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Horticultural production is reaching new heights every year, with India being the second-largest vegetable producer globally after China. Despite this, significant postharvest losses occur due to improper management and handling, exacerbating global challenges of food security, hunger, malnutrition and climate change. The United Nations' Sustainable Development Goal 2 aims to reduce food losses by 50% by 2030. This review highlights strategies to enhance the storability of fresh vegetables, including value addition through drying technology, temperature and storage atmosphere control and the use of anti-senescent molecules such as salicylic acid, nitric oxide, 1-methylcyclopropene and methyl jasmonate. In India, horticulture contributes 30% to agricultural Gross Domestic Product (GDP) from 8.5% of the cropped area, with a significant portion of produce being fruits and vegetables. Effective postharvest management and value addition can transform waste into wealth, reduce production costs and optimize biomass utilization. Technologies like drying, dehydration, freezing, fermentation and extraction are essential for recycling and upgrading vegetable market waste. This review provides a comprehensive overview of postharvest losses and potential strategies for reducing losses in vegetables, emphasizing the need for cost-effective technologies tailored to Indian conditions.

Key Words: *Horticulture; Post harvest management; Post harvest losses; Value addition; Biomass*

INTRODUCTION

The horticultural sector holds significant potential for the development of wastelands through well-planned system. Compared to traditional food crops, horticultural crops require comparatively less water, provide higher employment opportunities and are more environment-friendly. From the perspective of nutritional security, fruits and vegetables be prominent due to their potential for value addition, which not only enhances their market value but also contributes substantially to foreign exchange earnings. The horticultural crops are thus not only agricultural products but pivotal commodities in commerce, having gained substantial market potential globally. In the context of the Indian agricultural economy, horticultural crops have a significant role, contributing approximately 30% to the GDP from just 11.73% of the total arable land area. This sector is second only to China in terms of production, making India one of the leading producers of fruits and vegetables globally. In 2012, India's food processing industry was valued at around $ 70 billion, with the country producing 257 million tons of food grains, 75 million tons of fruits and 149 million tons of vegetables. Despite this strong production, India faces significant challenges with post-harvest losses, which are alarmingly high, vary from 30% to 40% for fruits and vegetables. This clearly contrasts with the lower post-harvest losses observed in countries like the United States of America and China, highlighting the urgent need for improved post-harvest management and value addition systems in India [1]. The high rate of post-harvest losses in India can be attributed to various factors, including inadequate infrastructure, inefficient supply chains and insufficient processing facilities. These losses not only reduce the net availability of produce but also represent a significant economic drain, estimated at Rs. 23,000 crores annually. The Swaminathan Committee reported that post-harvest handling accounts for 20%-30% of losses at different stages, including storage, grading, packing, transport and marketing. Furthermore, according to Chadha, India loses about 35%-45% of harvested fruits and vegetables during handling and storage, leading to annual losses of Rs. 40,000 crores [2]. The specific post-harvest losses for various fruits and vegetables further illustrate the severity of the issue: papaya (40%), grapes (27%), banana (20%-28%), citrus (20%-95%), avocado (43%) and apple (14%). Similarly, vegetable losses include onion (25%-40%), garlic (8%-22%), potato (30%-40%), tomato (5%-47%), cabbage and cauliflower (7.08%-25%), chili (4%-35%), radish (3%-5%) and carrot (5%-9%).

Despite these challenges, there are potential opportunities for enhancing the value of horticultural produce through various post-harvest technologies and practices. The diverse group of vegetables produced in India offers significant nutritional and health benefits, including essential vitamins, minerals and dietary fiber. These nutritional benefits are complemented by the presence of various phytochemicals that help in maintaining good health and preventing numerous diseases. Specific vegetable families such as cucurbits (e.g. bottle gourd, bitter gourd, cucumber), solanaceous vegetables (e.g. tomato, brinjal, chili), leguminous vegetables (e.g. Indian bean, French bean, pea), leafy vegetables (e.g. spinach, amaranth, fenugreek), cruciferous vegetables (e.g. cauliflower, cabbage, broccoli) and umbelliferae (e.g. carrot) are powerhouses of these beneficial compounds. To address post-harvest losses and enhance the value addition of horticultural produce, various drying technologies have been explored. Techniques such as hot air-controlled drying, spray drying, freeze drying, infrared drying, superheated steam drying, osmotic dehydration, microwave drying and hybrid drying methods are among the most notable. Freeze drying, although producing the best quality dried produce, has limitations such as longer drying times and higher energy consumption, making it cost-prohibitive for large-scale operations. On the other hand, hot air drying is widely used due to its cost-efficiency and ease of handling, although it may not always preserve the quality of the produce as effectively as freeze drying [3]. Moreover, several innovative post-harvest technologies have been developed to increase the shelf life of fresh produce. These include minimal processing, edible coatings, modified atmosphere packaging, ethylene absorbents, essential oils and hurdle technology. Other advanced methods involve the use of 1-methylcyclopropene, polyamines, salicylic acid, nitric oxide, 6-benzylaminopurine, methyl jasmonate and other anti-senescent molecules, all of which have shown in extending the freshness and shelf life of vegetables [4,5]. The commercial potential of vegetable-based processed products is immense, driven by their taste, health and nutritional benefits. The Indian Council of Agricultural Research (ICAR)-Indian Institute of Vegetable Research (IIVR) at Varanasi has been at the forefront of developing various vegetable-based processed products such as green chili powder, dehydrated okra, bitter gourd chips, instant bottle gourd kheer mix, instant moringa soup mix and instant moringa drink mix. These innovations have been patented and commercialized, providing a viable solution to reduce post-harvest losses and wastage. These developments underscore the need for a greater focus on secondary agriculture to increase employment,

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income and reduce losses, thereby promoting self-reliance and supporting agricultural start-ups [6].

Despite these advancements, a significant gap remains between the gross production of fruits and vegetables and their net availability due to post-harvest losses. The reasons for these losses are multifaceted, encompassing poor facilities, inadequate management, market dysfunctions and occasional carelessness by farmers. Therefore, it is essential to address these issues comprehensively to enhance the efficiency of the supply chain and improve the overall post-harvest management system. The present study aims to explore and discuss the critical issues related to post-harvest management of fruits and vegetables in India, with a particular focus on value addition. By reviewing existing literature and assessing the current state of post-harvest technologies and practices, this study seeks to provide actionable insights and recommendations to reduce post-harvest losses and enhance the value addition of horticultural produce. Such efforts are important for improving the economic viability of horticultural farming, ensuring better nutritional security and contributing to the sustainable development of the agricultural sector in India.

LITERATURE REVIEW

Losses after harvesting

Fruits and vegetables, characterized by their high moisture content, tender texture and high perishability, present a unique set of challenges in post-harvest management. If not handled properly, these highly nutritious products can deteriorate and become rotten within a matter of days or even hours. In the agricultural economy, horticultural crops are not only vital for nutritional security but also generate significant cash income for growers compared to cereals and pulses. The natural respiration process in these crops involves the crisis of food reserves and the aging of these organs, leading to their rapid decline if post-harvest practices are inadequate. Mechanical injuries are a major concern due to the tender texture and high moisture content of fruits and vegetables. Poor handling, unsuitable containers, improper packaging and transportation can easily cause bruising, cutting, breaking and other forms of mechanical injury. These damages significantly reduce the storability and market value of the produce. Physiological deterioration also plays a critical role post-harvest, as the cells of fruits and vegetables remain active and continue their physiological activities. This can lead to disorders caused by mineral deficiencies, temperature injuries or undesirable atmospheric conditions such as high humidity. Enzymatic actions further exacerbate physiological deterioration, resulting in over-ripeness and senescence. The importance of proper harvesting techniques cannot be overstated. Vegetables must be harvested at the correct maturity stage to achieve maximum quality. Harvesting at either pre-maturity or post-maturity stages, coupled with improper handling methods, significantly increases losses. Rough handling during and after harvest often results in mechanical injuries such as bruising, scarring, scuffing, cutting or puncturing the vegetables, thereby lowering their storability and quality. Post-harvest processing typically includes harvesting, sorting, grading and washing. The types of packaging materials used and the methods of transportation play critical roles in determining the extent of post-harvest losses. Farmers often use wooden baskets, gunny bags and plastic crates for packaging, with mini-trucks or lorries being common modes of transport. However, the increased use of corrugated cartons, especially ventilated Corrugated Fiberboard (CFB) boxes, for local distribution has been found to reduce bruising and other mechanical injuries, thereby preserving the quality of the vegetables [7].

Storage conditions also have a significant impact on the longevity of stored vegetables. Optimal storage temperatures can slow down aging, softening, color changes, undesirable metabolic shifts, moisture loss and pathogen-related losses. On-farm storage is particularly critical in remote and inaccessible areas of India, where high perishable vegetables are prone to losses. Proper cold chain management, which includes immediate cooling after harvest and maintenance during transport, is essential. However, the lack of cold storage facilities, coupled with the high cost and energy requirements of refrigeration, poses significant challenges. To address this, low-cost, zero-energy, environmentally friendly cool chambers, such as the Pusa Zero Energy Cool Chamber (Pusa ZECC), have been fabricated from locally available materials and operate on the principle of evaporative cooling. The issue of post-harvest losses is a serious concern for India's agricultural sector, particularly given the highly perishable nature of vegetables. Losses occur due to insufficient methods of harvest, decay, over-ripening, mechanical injury, weight loss, trimming and sprouting. Addressing these aspects is critical for improving the vegetable industry, especially in the context of processing and marketing [8]. Poor planning and lack of market information can lead to overproduction, which in turn results in unsold produce due to inadequate transportation and storage facilities. Additionally, improper preservation methods at home, such as methods of cooking and preparation like peeling, also contribute to these losses. Fruits and vegetables are rich sources of vitamins and minerals essential for human nutrition. However, the loss of these nutritious foods during transit from harvest to consumer represents a significant loss in valuable food quantity. In developing countries, up to 23% of perishable foods spoil due to inadequate cooling. Proper storage temperature management can improve time management and allow for leisurely marketing and consumption. In developed countries, maintaining cold storage temperatures, coupled with relative humidity throughout the entire supply chain from farm to consumer, significantly extends the shelf life of vegetables [9]. Conversely, inadequate storage facilities in developing countries remain a primary cause of post-harvest losses. Transportation presents another significant challenge, especially in the context of globalized food trade. Long-distance transportation with poor refrigerated facilities can lead to substantial losses in both quality and quantity, particularly for fresh produce. Developed countries typically employ refrigerated vehicles for perishable food delivery, whereas inadequate transport and inefficient logistics in developing nations hinder proper preservation. Furthermore, vegetables often suffer from inadequate packaging and careless loading practices, sometimes being haphazardly tossed into vehicles. Effective packaging and refrigerated transport significantly reduce losses and extend shelf life. Studies in Sub-Saharan Africa and South Asia highlight concerning statistics, with 46% of horticultural crops packed in cloth bundles or large sacks, 31% in open baskets and 8% having no packaging at all. At the retail stage, the absence of proper packaging further shortens the shelf life of vegetables, necessitating quick sales. Major challenges include cold chain management, the non-availability of mechanized sorting/grading facilities, the lack of varieties suitable for processing and inefficiencies in the complete value chain of vegetables [10]. The consumption stage, from purchasing to actual consumption is another phase where significant losses occur. Nearly half of household food waste consists of fruits and vegetables. Studies from the Food and Agriculture Organization (FAO) suggest that fruit and vegetable waste constitutes around 39%-40% of total household waste. Reasons for consumer waste vary from over-purchasing and poor planning to inadequate home-storage management. Socio-cultural factors such as gender, lifestyle, income and the availability of home storage facilities also influence the extent of waste [11].

Post-harvest losses in developed nations are often linked to consumer preferences, especially stringent quality standards and safety requirements for fruits and vegetables [12]. These losses are significant not only in quantitative terms but also from the perspective of quality nutrition. Careless harvesting and rough handling of perishable produce can result in bruising and scarring, reducing the quality and market price. Damaged produce also fails to attract international buyers, resulting in economic losses and a tarnished reputation for the exporting country. This degradation in both quantity and quality of food production from harvest to consumption impacts the nutrient/caloric composition, acceptability and edibility of the products. To improve the situation, it is essential to create awareness among growers, farm workers, managers, traders and exporters about the extent of losses being incurred and their economic consequences. These stakeholders need to learn the basic principles of fruit handling and storage. With increasing consumer consciousness about health and nutrition, there is a growing tendency to avoid chemicals and synthetic foods in favor of natural resources. Underutilized fruits such as aonla, bael, jamun, karonda, passion fruit, phalsa, pomegranate, pumpkin, tamarind and wood apple play an essential role in overcoming malnutrition and provide a primary livelihood source for the poor.

Mitigating post-harvest losses in horticulture: Strategies and innovations

The significant issue of post-harvest losses in the vegetable supply chain presents a multifaceted challenge impacting food security, economic stability and the livelihood of farmers globally, particularly in developing countries like India. Effective post-harvest management, encompassing a wide array of activities such as cleaning, washing, sorting, grading, disinfecting, packaging and storage at optimum temperatures, is critical for preserving the edible and nutritional quality of vegetables for extended periods. This approach

not only supports the sustenance of farmers but also enhances the overall efficiency of the food supply chain [13].

Post-harvest management activities

Post-harvest management involves several key processes. Sorting and grading are vital steps where diseased, damaged, over-mature, insect-infested and rotten vegetables are removed, ensuring only high-quality produce reaches consumers. Standardized grading criteria further enhance product consistency, improving market positioning and consumer trust. Washing vegetables eliminates contaminants such as dirt, dust, insects, mold and any residual sprays, thus enhancing their appearance and hygiene. The application of chlorinated water (100-150 ppm) or saltwater (1%-2%) can effectively reduce surface contaminants. Disinfectants like chlorinated water at pH 6.5-7.5 are employed to control inoculum in packing houses during storage [14,15].

Packaging of vegetables

In India, fresh vegetables are typically packaged and transported in perforated plastic crates, gunny bags and bamboo baskets. Softer vegetables often require cushioning with dry grass, banana leaves or paper shreds to prevent damage. Consumer packages may include plastic bags and shrink wraps with or without consumer trays, usually made of foam or plastic. Advanced packaging materials, such as plastic films and waxed liners, provide additional protection. Packaging is generally categorized into consumer units or pre-packaging, transport packaging and unit load packaging or pallets.

DISCUSSION

Challenges with specific vegetables

Broccoli for instance, has a limited shelf life due to its high respiration rates, leading to quick degradation of chlorophyll, flower bud opening, loss of turgidity, off-flavor development and nutritional quality loss. However, the use of Flexfresh™ packaging material, which creates a modified atmosphere during storage at 3°C, has been shown to extend the shelf life of broccoli florets to 49 days. Similarly, capsicum stored in Flexfresh™ expanded polyethylene biopolymer pouches saw increased shelf life and acceptability. Bitter gourd fruits packed in corrugated fiberboard boxes with potassium permanganate sachets exhibited the lowest degradation in fruit quality over an 8-day storage period at room temperature.

Edible coatings

Edible coatings, such as chitosan, cellulose, starch, gums, beeswax and protein-based coatings like gelatin and soy proteins, offer another layer of protection. These coatings reduce moisture loss, slow down respiration, senescence and enzyme activity, preserve natural color, flavor and texture and protect against microbial growth. Application methods include spraying, dipping, smearing or brushing directly onto the vegetable surface, followed by drying to form a protective layer. The efficacy of these coatings depends on various factors, including the materials used, temperature, thickness and type of vegetable. Approved edible coatings enhance shelf life and maintain the quality of various vegetables, including tomatoes, cucumbers and eggplants [16].

1-methylcyclopropene

1-Methylcyclopropene (1-MCP) is an ethylene antagonist that delays natural ripening and aging processes in vegetables. By binding to ethylene receptors, 1-MCP blocks the signaling responsible for ripening, thereby extending the shelf life of produce like cucumbers, tomatoes and peppers. It is recognized for use in over 50 countries and can be applied through various methods, including gaseous treatment, fumigation and aqueous solution dipping.

Value addition

Value addition through drying offers significant opportunities for vegetable preservation. Despite potential innovation and diversification in the vegetable sector, many Small and Medium Enterprises (SMEs) struggle with upscaling, technology access and compliance with international standards. Traditional processing methods, such as drying, can transform perishable vegetables into shelf-stable products, creating new market opportunities and fostering entrepreneurship. For instance, drying techniques can be applied to vegetables like bitter gourd, cauliflower, carrot and broccoli, yielding high-quality, value-added products [1].

Minimal processing

Minimal processing techniques for fresh-cut vegetables are popular due to their fresh-like characteristics, safety and quality. These techniques include cleaning, trimming, slicing, shredding, dicing, sanitizing and packaging. However, processing can cause tissue damage, hasten microbial growth and spoilage, necessitating rigorous sanitation and careful process hygiene. Maintaining a consistent cold chain and employing preservation techniques like chemical preservatives, mild heat treatment and vacuum packaging are significant for minimal processing.

Drying techniques

Drying is a cost-effective method for producing shelf-stable products. Techniques such as solar drying, osmotic dehydration, microwave drying and freeze drying offer various benefits. For instance, osmotic dehydration uses hypertonic solutions for partial moisture removal, resulting in effective drying and rehydration with low energy consumption and high product quality. Microwave drying provides quick and uniform drying, while freeze drying retains maximum quality in the final product but consumes significant energy. These techniques can significantly reduce post-harvest losses and ensure nutritional security [17].

Ready-to-eat convenience products

The demand for ready-to-eat convenience products is growing due to lifestyle changes and increased awareness of health foods. Products like bitter gourd chips and instant bottle gourd kheer mix offer innovative solutions to post-harvest loss while providing consumers with nutritious and convenient options. ICAR-IIVR has developed several vegetable-based convenience products that can be stored for extended periods and reconstituted quickly, addressing both post-harvest losses and consumer needs [1].

The future of post-harvest management and value addition

The future of post-harvest management and value addition in vegetables looks potential for enhancing food security, economic growth and agricultural sustainability. Processing techniques such as freezing, drying and fermentation can transform perishable vegetables into long-lasting products. Investment in research and development, improved infrastructure and innovative processing methods are key to unlocking the full potential of value addition in vegetable crops. These advancements will contribute to economic development, self-reliance and the growing demand for nutritious and high-quality produce.

CONCLUSION

The current scenario underscores significant challenges in post-harvest management and the underutilization of value-addition techniques. However, the potential for innovation and market diversification is vast. Effective post-harvest management and value addition can reduce food wastage, enhance the economic value of vegetables and create new market opportunities. Collaborative efforts in research, technology and policy support are essential to realizing these prospects. By harnessing these opportunities, the agricultural sector can achieve improved sustainability, economic viability for farmers and enriched consumer choices, ensuring a brighter future for vegetable crop management. This introduction sets the stage for a comprehensive exploration of post-harvest management and value addition in vegetables, emphasizing the need for innovative approaches to enhance food security, economic stability and sustainability in agriculture.

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