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Sustainable Strategies for Post-Harvest Management and Utilization of Horticultural Surplus in India

Arun Thakur, Suman Bodh*, Praveen Verma and Parikshit Verma

Department of Horticulture, School of Agriculture, Lovely Professional University, Phagwara, Punjab, 144401, India

ABSTRACT

Post-harvest management and sustainable utilization of surplus horticultural produce are vital for addressing food security, reducing agricultural waste, and promoting environmental sustainability. Fruits and vegetables, being highly perishable face significant post-harvest losses impacting economic stability and environmental health. With a growing global population and strained natural resources, innovative strategies are essential to extend shelf life, minimize waste, and create economic value. This review focuses on two objectives: first, assessing current post-harvest management practices including advanced storage technologies, packaging innovations and treatments to maintain quality and reduce losses. Techniques such as cold storage, modified atmosphere packaging, and chemical/biological treatments are examined. Second, it explores sustainable approaches to transform surplus produce into value-added products like processed foods, bio-based materials and industrial goods. Emerging technologies, including edible coatings, nanotechnology and precision agriculture, offer promising solutions to minimize losses. The review highlights critical research and practice gaps, emphasizing the need for integrated approaches that consider environmental, economic, and social dimensions. However, scaling these technologies faces persistent challenges, including economic barriers, infrastructure gaps, and technical limitations in resource-constrained regions. Furthermore, achieving optimal trade-offs between treatment efficacy, safety compliance, and consumer acceptability of novel solutions remains scientifically and commercially challenging. Effective post-harvest management and surplus utilization enhance resource efficiency, reduce waste and contribute to a sustainable agricultural system. Investments in research, infrastructure, and policy frameworks are crucial to improving post-harvest systems and fostering a circular economy in horticulture, driving innovation, reducing waste, and promoting sustainability for economic and environmental benefits.

Keywords: *Agri-food system, Cold chain, Environment, Food security, Horticulture, Post-harvest, Preservation, Sustainable utilization, Surplus production, Value addition*

Introduction

The global population is rapidly increasing and is projected to continue doing so for the rest of this century. Research suggests an 80 per cent likelihood that by 2100, the world's population will rise from 7.2 billion to between 9.6 and 12.3 billion [20]. With this growth comes a significant surge in food demand, particularly as the middle class in developing countries becomes wealthier. It's estimated that global food demand could increase by 50 per-cent to 70 per-cent by the middle of this century [10][22][71]. Horticultural products, such as fruits and vegetables, are essential for a healthy diet, providing critical nutrients that help combat hunger and improve food security. However, despite awareness efforts, the consumption of fruits and vegetables remains lower than recommended. The daily requirement for a healthy life is between 150 g/day to 400 g/day [76], but meeting this need is challenging for a large portion of the global population. This growing demand for food combined with the pressures of urbanization and shifting dietary preferences in developing nations, is straining the planet's resources. Agricultural lands are degrading, freshwater supplies are depleting, and biodiversity is declining under this stress. Climate change compounds these challenges creating a complex web of environmental issues [50]. To address these critical challenges, we need a comprehensive and innovative approach to sustainable food production. This includes embracing technological innovations such as crop genetic advancements, better irrigation methods, and improved post-harvest storage to minimize waste. Sustainable resource management practices are also essential to balance the growing food demand with environmental conservation [70]. Globally an estimated 1.3 billion tons of food are lost each year [27], underscoring the severity of food waste as a barrier to food security. As the world's population is expected to reach 10.5 billion by 2050, this issue is increasingly urgent. Food loss not only undermines food security but also contributes to environmental degradation by wasting water, energy, and land used in food production. Moreover, it accounts for roughly 8 percent of global greenhouse gas emissions, exacerbating climate change [96]. Addressing these interconnected issues through holistic strategies is crucial to ensuring food security and sustainability for future generations.

*Corresponding Author: ***Suman Bodh***

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Post-harvest losses in horticulture

Post-harvest losses pose a major obstacle in horticultural supply chains, especially in developing countries. These losses not only threaten food security but also directly affect farmers' livelihoods with estimates showing that up to 10 to 40 percent of horticultural production is loss in certain regions [6].

Various factors contribute to Post-harvest losses including inadequate storage, poor handling practices, and technological gaps in post-harvest management shown in figure 1 [9]. A significant global challenge stems from postharvest losses and waste, impacting both the quantity of horticultural produce shown in Table 1 and Table 2. These losses include measurable factors like weight and size as well as qualitative aspects such as taste and nutritional value. Effective management requires proper handling the use of postharvest technologies and considering social factors. While aiming for zero losses is ideal, practical and economic realities mean accepting some level of loss is necessary [105].It is estimated that excluding waste that occurs after consumption almost one-third of all fruits and vegetables produced worldwide are lost after harvest. With the exception of food left in the field for visual and quality reasons, a report says that postharvest losses in the UK are estimated to be approximately 9 per cent from harvest to retailer [37]. Fruit and vegetable losses in the US in 2008 totalled $42.8 billion or almost $141 per person, at the retail and consumer levels [11]. These numbers highlight the negative impact of postharvest losses on the economy and nutrition, highlighting the need for focused initiatives throughout the supply chain to successfully reduce these losses.

Table 1. Post-harvest losses in horticulture in India (NABCONS 2022).

Crops/ Commodities	Loss (%)	
	As per ICAR-CIPHET Study (2015)	As per NABCONS study (2022)
Fruits	6.70-15.88	6.02-15.05
Vegetables	4.58-12.44	4.87-11.61
Plantation Crops & Spices	1.18-7.89	1.29-7.33

Table 2. Post-harvest losses of various crops in India

Crop Type	Crop	Post-harvest Losses (%)	Reference
Fruits	Papaya	7 - 15%	NABARD Consultancy Services 2022
	Guava	6.74%	Ministry of Food Processing Industries 2022
	Mango	8 - 14%	NABARD Consultancy Services 2022
	Pomegranate	10 - 12%	NABARD Consultancy Services 2022
	Grape	8 - 12%	NABARD Consultancy Services 2022, FAO 2022
Vegetables	Tapioca	5 - 9%	FAO 2022
	Tomatoes	4.87 - 11.61%	Ministry of Food Processing Industries 2022
	Cauliflower	6 - 10%	NABARD Consultancy Services 2022
	Brinjal	4.87 - 9%	Ministry of Food Processing Industries 2022
	Potato	5 - 7.5%	NABARD Consultancy Services 2022
Plantation crop/ spices	Arecanut	3 - 5%	FAO 2022
	Black pepper	6%	Ministry of Food Processing Industries 2022
	Coriander	5 - 7%	NABARD Consultancy Services 2022
	Cashew	5 - 9%	FAO 2022
Oilseed	Soybean	2.87 - 5.92%	Ministry of Food Processing Industries 2022
	Sunflower	3 - 5%	NABARD Consultancy Services 2022

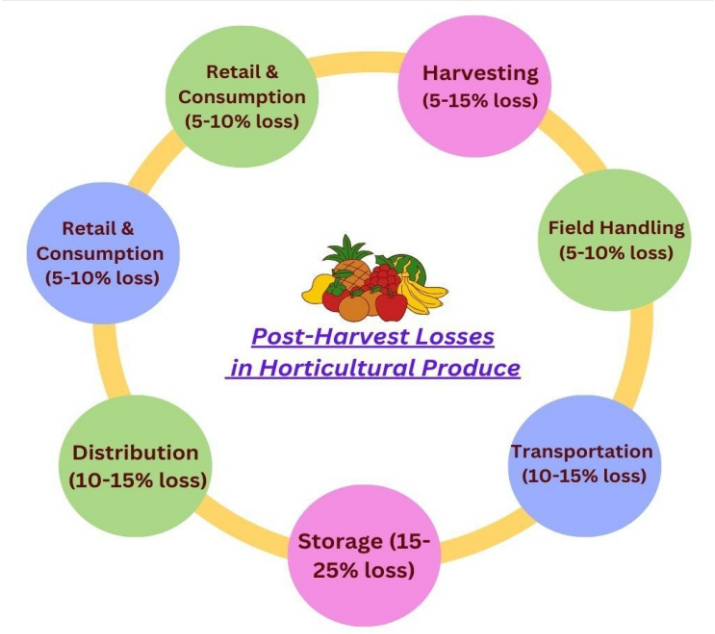

Fig. 1 Post-Harvest Losses in Horticultural Produce

Surplus production

India, a prominent global producer of fruits and vegetables frequently encounters surplus horticultural production. This surplus is primarily driven by advancements in agricultural technology, favourable climatic conditions, and the introduction of high-yielding crop varieties. While this production surplus underscores the success of Indian agriculture, it presents notable challenges including price crashes, economic losses for farmers, and considerable post-harvest wastage. For instance, states like Maharashtra and Andhra Pradesh often experience market gluts during peak tomato production seasons leading to drastic price drops. Farmers, unable to secure profitable prices for their produce sometimes leave crops unharvested, which contributes significantly to food loss [32]. Additionally, India's supply chain infrastructure remains inadequate; limited cold storage facilities and suboptimal transportation exacerbate wastage with a substantial portion of surplus horticultural produce spoiling before reaching consumers. According to the Indian Council of Agricultural Research approximately 30 percent of India's horticultural produce is wasted annually due to inefficient post-harvest management [32]. Several other factors contribute to the surplus in horticulture. Seasonal overproduction is a notable issue, as certain fruits and

vegetables are harvested in high volumes during specific seasons, leading to gluts [98]. Market fluctuations also play a critical role; imbalances between supply and demand often lead to surplus production when consumer preferences and market trends shift unexpectedly leaving producers with excess stock [31]. Aesthetic standards contribute further as a substantial amount of produce is discarded due to cosmetic imperfections despite being nutritionally sound [60]. Lastly, inefficiencies within the supply chain, including inadequate transportation, storage, and distribution infrastructure, significantly contribute to spoilage, particularly in developing regions. These inefficiencies are often aggravated by poor market conditions and a lack of price information, which complicates the timely and effective distribution of produce [77]. While these factors illustrate the challenges associated with surplus horticultural production, there is growing recognition of the potential for innovative recovery and reuse techniques. Harnessing surplus produce through strategies such as processing, bio-waste conversion or alternative markets could contribute to a more sustainable and resilient agricultural system [77].

Effect of surplus horticultural produce on the environment

The issue of surplus horticultural produce presents significant environmental challenges, particularly in terms of greenhouse gas emissions, resource inefficiencies, and ecosystem degradation [99]. Due to overproduction, seasonal fluctuations, and distributional inefficiencies, substantial quantities of fruits, vegetables, and other perishable horticultural products often go unsold contributing to substantial waste [83]. This excessive waste not only represents lost economic value but also has considerable environmental consequences. A major environmental concern is the release of greenhouse gases during the decomposition of surplus produce. In landfill environments this organic matter decomposes anaerobically leading to methane emissions, a greenhouse gas with a global warming potential approximately 25 times higher than carbon dioxide [33]. Methane emissions from decomposing organic waste exacerbate climate change, which is already impacting India and other countries as well through altered precipitation patterns, increased drought frequency, and intensified extreme weather events [87]. Resource wastage associated with surplus horticultural produce is also a pressing ecological concern. Producing horticultural crops requires intensive use of water, energy, and fertilizers. The loss of produce translates directly into wasted inputs, further straining India's critical water resources and energy supplies. Given the nation's water scarcity and reliance on agricultural withdrawals, inefficient resource use exacerbates water stress, threatening long-term water security [62]. Additionally, decomposing horticultural waste can lead to nutrient leaching, which affects both soil and water quality. The runoff from decomposed biomass contributes to eutrophication in nearby water bodies, causing hypoxic conditions that significantly disrupt aquatic ecosystems. This nutrient pollution intensifies existing issues with river and groundwater contamination, with adverse effects on biodiversity and water quality [12]. The disposal of surplus produce also involves additional transportation and handling, increasing fossil fuel consumption and associated carbon emissions shown in figure 2. Addressing these environmental impacts requires systemic improvements, including investments in cold storage, efficient distribution systems, and the adoption of circular economy principles to repurpose surplus produce [19].

Policy frameworks that promote sustainable resource utilization and effective waste management practices are essential. Improved handling of horticultural surpluses is critical for India to mitigate environmental degradation and transition to a more sustainable agricultural model .

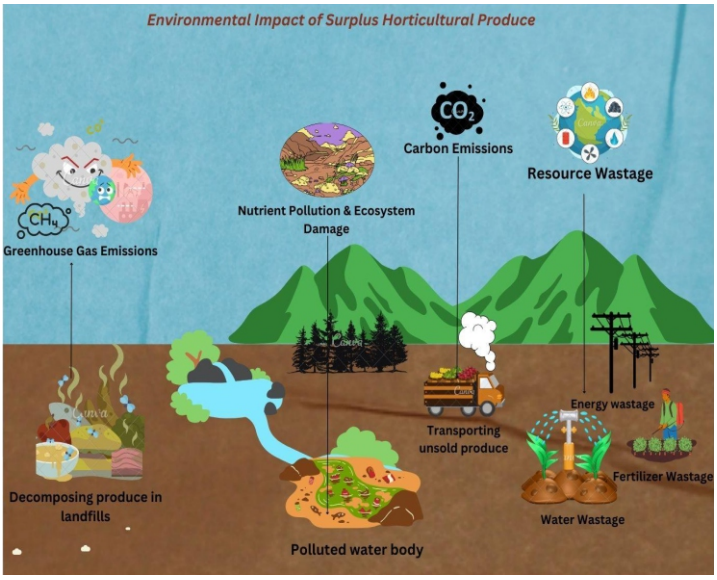

Fig. 2. Effect of surplus horticultural produce on environment

Sustainable utilization practices

Sustainable post-harvest handling techniques

Worldwide, food loss and waste represent serious issues. Roughly one-third of all food produced is wasted after harvest. This also results in an enormous waste of labour, land, fertilizers, water and other resources [41]. Moreover, food waste decomposition increases greenhouse gas emissions. Sustainable post-harvest handling techniques are essential for minimizing losses in horticultural produce, enhancing food security, and promoting economic growth. Effective management practices can significantly reduce waste and improve the quality of fruits and vegetables, which is crucial in a world facing hunger and environmental challenges. Harvesting at the right maturity stage is vital to prolong storage life and maintain quality [34]. Inadequate handling and packaging contribute significantly to post-harvest losses, necessitating the adoption of advanced technologies [9].

Optimizing resource efficiency: sustainable post-harvest handling techniques

In order to minimize food waste and guarantee food security, it is essential to optimize resource utilization during the post-harvest phase of food production [1]. It is critical to use modern technologies, such as artificial intelligence systems to reduce waste throughout the harvest and post-harvest processes by avoiding human error and making educated judgments [92]. Research indicates that various factors, including the age of the mill, experience, storage space, distance to market, servicing, and energy type, have an impact on post-harvest efficiency. To mitigate these effects, policy interventions such as investing in storage facilities, drying technologies, improved miller technologies, dependable energy sources, and workshops can be implemented [93]. Decision-makers can maximize profit by using mixed-integer programming models to optimize resource allocation, equipment selection, and harvest planning and contributing to efficient post-harvest resource management.

Value addition and processing

Value addition and processing technologies play a pivotal role in transforming surplus produce and extracting maximum value from by-products in the Horticultural sector [90] . Value addition aim to enhance economic returns, better life style, reduce waste and contributing to sustainable agricultural practices as shown in figure 3 [88]. Processing technologies serve as a crucial bridge between surplus produce and consumer-ready goods. Techniques such as canning, dehydration, and freeze-drying extend the shelf life of fruits and vegetables, enabling the preservation of nutritional content beyond the harvest season [88]. This not only addresses the challenge of surplus produce but also ensures a year-round supply of nutritious food. Moreover, extracting value from by-products contributes to a circular and sustainable economy [23]. Horticulture-industrial by-products, often considered waste, can be transformed into valuable commodities through innovative processing methods. For instance, By-products from fruits, vegetables and other horticultural crops can be processed to extract and concentrate bioactive compounds, which can then be used as ingredients in the formulation of nutraceuticals and functional foods. This helps to add value to the by-products and reduces waste [35]. This not only minimizes waste but also generates additional revenue streams for farmers and processors. Processing technologies enable the creation of diverse products, catering to changing consumer preferences. From fruit juices and jams to dehydrated snacks, the versatility of processing techniques allows for the development of a wide range of marketable products [48]. This diversification contributes to a resilient agricultural sector by reducing dependency on a single commodity and mitigating the impact of market fluctuations. Value addition and processing technologies are indispensable tools for addressing surplus produce and harnessing the untapped potential of agricultural by-products. These practices not only enhance economic returns for stakeholders but also align with the principles of sustainability and circular economy.

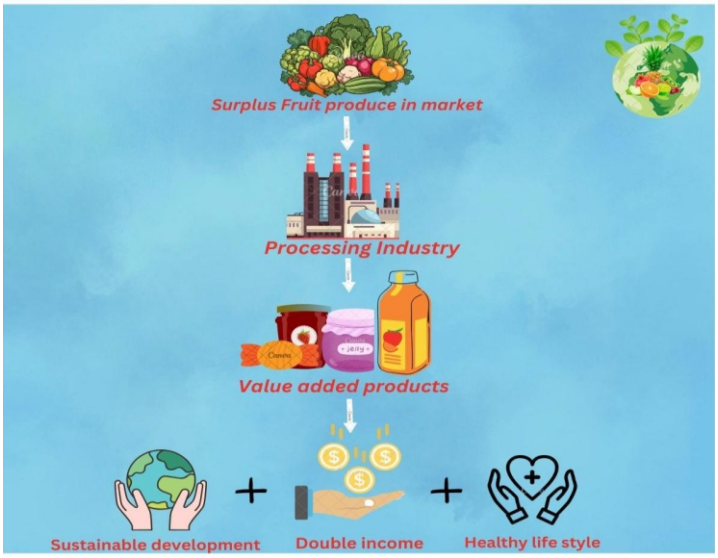

Fig.3. Value addition in surplus fruit produce

The surplus produce from horticultural activities can be effectively utilized in various sustainable ways, including bioenergy production, animal feed, and composting. These methods not only minimize waste but also contribute to environmental sustainability and economic efficiency in agriculture.

Bioenergy production

Surplus horticultural waste can be converted into renewable energy through anaerobic digestion, producing biogas and bioethanol. Biogas plants can transform organic waste into energy and nutrient-rich fertilizers, benefiting rural communities [57]. For instance, citrus waste can yield significant biogas, with methane concentrations reaching 54.90% [26]. Additionally, agricultural residues can be processed into bioethanol, enhancing fuel quality and reducing emissions (Hamdi et al 2024).

Animal feed

Surplus fruits and vegetables, particularly those unsuitable for human consumption, can serve as livestock feed. This practice reduces reliance on grain-based feeds lowering costs for farmers and promoting circular farming [57]. Utilizing such waste contributes to sustainable livestock management and resource efficiency.

Composting

Composting is a sustainable method for managing horticultural surplus. Organic waste decomposes into nutrient-rich compost, enhancing soil quality and supporting sustainable agriculture [57]. This process not only reduces landfill waste but also improves agricultural productivity. While these methods present significant benefits, challenges such as the need for proper infrastructure and market acceptance for bioenergy and animal feed must be addressed to maximize their potential.

Challenges in implementation

Infrastructure hurdles

Adoption of new technology is difficult in some countries like the adoption of post-harvest technology in India is made difficult by infrastructure, which presents serious problems . The majority of the research that is now available focuses on productivity enhancement rather than post-harvest losses [74]. Agri-startups encounter challenges in cold storage operations since different commodities demand different temperatures. Significant food losses and wastage during the post-harvest stages pose a danger to global food security, underscoring the need for smart post-harvest handling and processing systems. The economic and welfare losses resulting from product spoiling in India highlight the pressing need to address obstacles such as insufficient government assistance and transportation infrastructure. It is imperative to employ technology and improve supply chain management to overcome these infrastructure obstacles in order to reduce post-harvest losses and increase food security in India.

Socio-economic barriers

Overcoming socioeconomic barriers is necessary to address the post-harvest technology implementation issues. The mentioned barriers involve the requirement for governmental assistance, enhancement of transportation infrastructure establishment of minimum support prices, and management of financial deficits resulting from spoilage and quality-related problems in the post-harvest supply chain [64]. Indian Agri-startups are creating solutions for post-harvest and storage problems, including the need to store different commodities at different temperature ranges, reduce electricity costs and reduce their dependence on generators [74]. Additionally, improving food security and lowering food losses and waste depend heavily on developments in postharvest handling and processing

technology, such as smart practices, solar dryers, and active packaging [38]. India can effectively lower post-harvest losses, increase farmer profitability and increase rural employability by dealing with these socioeconomic barriers and utilizing technology innovations. [Grab your reader's attention with a great quote from the document or use this space to emphasize a key point. To place this text box anywhere on the page, just drag it.]

Technological Advances in post-harvest management

Innovations in technology aimed at reducing postharvest losses and improve the overall efficiency of the agricultural supply chain have grown considerably in recent years [104].

Storage technology

The evolution of storage technology has revolutionized the preservation of perishable produce through sophisticated environmental control systems and innovative monitoring solutions [102]. Modern controlled atmosphere storage (CAS) represents a significant advancement in preservation technology, utilizing precise atmospheric composition control and maintaining oxygen levels between 1-5%, carbon dioxide at 3-15%, nitrogen at 80-95% and ethylene below 1 ppm. These systems operate within carefully controlled temperature ranges from -1°C to 13°C, with relative humidity maintained at 85-95%, creating optimal conditions for prolonged storage while significantly reducing metabolic activity and preserving product quality and also the implementation of intelligent storage systems has demonstrated remarkable success in preserving post-harvest quality and reducing losses through sophisticated monitoring mechanisms [100]. These systems integrate cutting-edge IoT technology, employing RFID sensors for continuous tracking, quantum sensors capable of detecting ethylene at concentrations as low as 0.1 ppm and hyperspectral imaging for non-destructive quality assessment. AI-driven algorithms analyzethis data in real-time, enabling predictive spoilage prevention and optimal storage condition management, while blockchain integration ensures complete traceability throughout the storage process [94]. Recent innovations have introduced groundbreaking approaches to storage preservation. Photocatalytic systems utilizing Ti O_2-based materials and UV-C radiation (254 nm wavelength) provide effective microbial control. Bioelectric field storage, operating at 0.5-2.0 kV/cm and ultrasonic humidification systems generating 2-5 μm droplets at 20-100 kHz, offers unprecedented control over storage environments [47]. These technologies work synergistically with controlled atmosphere storage to slow physiological processes and prevent microbiological growth by maintaining precise control over environmental parameters [94]. The effectiveness of controlled atmosphere storage in extending post-harvest life while maintaining flavour, texture, and nutritional value has been well documented [101]. Research has shown significant reductions in ethylene production and respiration rates, effectively delaying ripening and senescence [103]. Furthermore, these systems minimize water loss to less than 2% of fresh weight and substantially reduce chilling injury risk, resulting in improved marketability . These comprehensive storage solutions have demonstrated remarkable results, achieving 30-50% increases in storage life, 40-60% reductions in post-harvest losses and 25-35% improvements in quality retention. The integration of smart packaging technologies, including antimicrobial packaging and specialized films, has further enhanced product preservation by controlling respiration rates, inhibiting microbial growth, and maintaining optimal storage conditions [16].

Packaging technology

Technological advancements in packaging are crucial for protecting products during transport and storage, as they serve as barriers against physical damage, microbiological contamination and oxidative processes [8]. In recent years, significant progress has been made with bio-based materials, active packaging technologies, intelligent packaging solutions. and vacuum packaging systems. These developments play a pivotal role in enhancing the safety, quality, and shelf life of perishable goods, particularly fruits and vegetables. The use of oxygen scavengers and antimicrobial agents within these packaging systems has proven beneficial in reducing spoilage, as these components actively inhibit microbial growth and minimize oxidative deterioration, thereby extending the longevity of products [14][25]. The integration of advanced packaging technologies especially in the horticultural sector has been recognized for its positive impact on product shelf life and quality. Among these innovations like nanotechnology and active packaging systems address the critical challenges associated with postharvest losses and spoilage in fresh produce. Nanotechnology has opened new avenues for packaging innovations, providing highly functional materials that enhance protective barriers. Antimicrobial nanomaterials, for instance, inhibit the growth of spoilage-causing microorganisms, thereby maintaining the quality of fruits and vegetables for a prolonged period [68] . Nanotechnology applications in packaging extend to the development of nanofilms, which regulate gas exchange and offer UV protection, further improving the storage conditions and quality of packaged items [68]. These films serve as a sophisticated approach to managing the internal environment of the packaging, creating a controlled atmosphere that mitigates deterioration. Active packaging techniques, such as interactive controls and dynamic modified atmosphere packaging, are also instrumental in managing the respiration rates and humidity levels of fresh produce. Interactive packaging adjusts to changes in the surrounding environment, effectively optimizing atmospheric conditions for the stored produce [86]. Dynamic modified atmosphere systems employ specialized materials to maintain an ideal internal atmosphere which helps reduce the rate of spoilage by controlling gas levels, thus extending the freshness of horticultural products during distribution and retail [80]. Despite the clear advantages offered by these advanced packaging solutions, there are challenges in ensuring their widespread adoption, particularly concerning the economic feasibility and accessibility across different horticultural sectors. Achieving cost-effective implementation remains essential to making these technologies viable on a larger scale. Addressing these economic and operational hurdles will be critical for advancing sustainable packaging solutions that benefit both consumers and the broader supply chain.

Cold chain systems

Cold chain systems are integral to preserving the freshness and quality of perishable food items from farm to table. These systems involve a continuous refrigeration process that helps maintain low temperatures throughout the supply chain, from

harvesting and processing to transport, storage and retail. Advances in refrigeration technology, temperature monitoring, and logistics have significantly improved the efficiency and reliability of cold chains, reduced temperature fluctuations and prevented premature spoilage [58]. Cold chain systems minimize postharvest losses by limiting the growth of spoilage bacteria and slowing down enzymatic and physiological processes that contribute to food degradation. Temperature monitoring technologies, such as RFID sensors and IoT-based solutions, play a crucial role in modern cold chains, allowing real-time tracking of temperature conditions and alerting stakeholders to deviations that could compromise product quality. These innovations are essential for ensuring that the cold chain remains unbroken, particularly during long-haul shipments and international distribution [5]. Maintaining a stable temperature range in cold chain systems is critical to safeguarding the quality and safety of perishables, as even slight temperature shifts can lead to microbial growth or nutrient loss, thus impacting both shelf life and food safety [27]. The importance of cold chains extends to global food distribution, as disruptions in these systems can result in substantial food losses, particularly for temperature-sensitive products like fruits, vegetables, dairy, and meats. Studies indicate that an uninterrupted cold chain can significantly reduce food spoilage and wastage, particularly in regions with long supply chains or extreme temperature variations. Effective management and planning of these systems, including optimizing storage and transportation practices are essential for maximizing efficiency and reducing the environmental impact of food wastage [45]. Overall, cold chain systems remain an indispensable component of food logistics, as they not only reduce waste but also support food security by ensuring that fresh, nutritious produce reaches consumers in optimal condition. In this regard, investing in cold chain infrastructure and enhancing technological capabilities will be pivotal in tackling global food waste challenges and improving the sustainability of the food supply chain [42].

Natural preservatives

The need for natural and environmentally friendly alternatives has inspired researchers to investigate bio-based preservatives [59]. Organic acids, plant extracts and essential oils are examples of natural substances with antibacterial qualities that offer a sustainable substitute for conventional chemical preservatives. The potential of natural preservatives to prevent spoiling organisms and preserving the taste and texture of food products [24]. Also, natural preservatives can increase the nutritional value and safety of foods thereby meeting consumer demand for so-called clean-label products. New packaging technologies such as incorporating natural preservatives into edible films and coatings, help to further extend the shelf life of perishable goods [46].

Market linkage and distribution

Market linkage and optimized distribution systems play an essential role in reducing postharvest losses in horticulture by enhancing access to markets, streamlining supply chains, and ensuring the quality of produce from farm to consumer. Effective strategies focus on improving handling, storage and transportation infrastructure as well as integrating advanced technologies to create a seamless and efficient pathway for horticultural goods [63][15][13]. A critical component of market linkage is establishing robust connections between farmers and diverse marketplaces enabling horticulture producers to reach a broader consumer base which promotes price stability and fosters competition. This enhanced connectivity benefits both farmers and consumers by stabilizing prices and improving market access [63]. In addition, strengthening supply chain management is vital for minimizing postharvest losses as timely transportation, proper storage and handling practices help prevent spoilage and degradation. Investments in cold storage facilities and reliable transportation networks are essential for preserving the freshness of perishable goods thereby supporting higher-quality produce and extending shelf life [37]. Optimized supply chain models further contribute to loss reduction by coordinating the roles of various stakeholders, including farmers, processors, distributors and retailers. Structured supply chains improve information flow and resource allocation creating a responsive and resilient network that adapts to market dynamics and reduces inefficiencies. Sustainable practices, such as the use of mixed-closed transportation methods also enhance environmental sustainability by reducing carbon emissions while preserving produce quality [13]. Adopting innovative technologies and sustainable practices strengthens market linkage and distribution efficiency. Advanced packaging solutions including biodegradable materials help maintain produce quality and reduce waste associated with conventional packaging [95]. Additionally, sensor technologies to monitor ripeness, temperature, and humidity enable real-time data collection allowing optimal handling and storage conditions that minimize losses due to premature spoilage. Studies show that these technologies, along with proper handling and storage practices like pre-cooling and sorting, can significantly reduce spoilage preserving both quality and value [43]. Implementing these strategies for improved market linkage and distribution infrastructure is crucial for fostering a sustainable and economically viable horticulture sector. By investing in technology, infrastructure, and collaborative supply chain models stakeholders can significantly mitigate postharvest losses ensuring a greater share of produce reaches consumers in optimal condition and enhancing the overall resilience of the horticulture supply chain [40].

Community and stakeholder involvement

Engaging communities

Engaging communities in horticulture can significantly reduce postharvest losses in India by fostering collaboration, enhancing knowledge sharing, and promoting sustainable practices. Community-driven efforts enable better management techniques, resource utilization and awareness of postharvest challenges, creating a more resilient and efficient agricultural landscape. Collaborative knowledge sharing is one such strategy; community-led training programs, including workshops on best practices for harvesting, handling and storage have shown the potential to reduce losses by up to 30 per cent sharma [82]. Peer learning also plays a critical role, as farmers sharing their experiences can inspire locally adapted innovative practices that improve both produce quality and shelf life [9]. Sustainable practices developed within communities are crucial for addressing local needs. These include adopting low-cost, eco-friendly technologies for packaging and storage, such as biodegradable materials which help maintain freshness and minimize environmental impact [95]. Communities can also focus on value addition, engaging members in small-scale processing activities like drying, pickling or making preserves effectively transforming surplus

produce into marketable products and reducing waste [69]. In addition, enhanced market access through collective marketing efforts such as forming cooperatives allows farmers to improve their bargaining power, access better markets, and decrease the risk of unsold produce [89]. Furthermore, communities can organize regular postharvest assessments and establish local collection centres to streamline supply chains ensuring produce reaches markets or processing centres more efficiently. By collaborating with local governments and NGO's communities can also access grants and resources to support infrastructure development which is essential for sustainable postharvest management. While these benefits are substantial, challenges such as disparities in education, resources, and infrastructure may hinder the full potential of these initiatives. Addressing these challenges is essential for maximizing the impact of community-driven efforts in minimizing postharvest losses and fostering long-term sustainability in Indian horticulture.

Stakeholder collaboration

Stakeholder collaboration is pivotal in reducing postharvest losses in Indian horticulture by facilitating effective communication, resource sharing and the adoption of innovative technologies. Involving diverse stakeholders' farmers, handlers, consumers and organizations enhances the supply chain's efficiency, minimizes waste, and promotes sustainable agricultural practices. Multi-stakeholder partnerships (MSPs) exemplify this collaborative approach, addressing postharvest challenges through coordinated efforts among various actors, including science, business, legislators and farmers [53]. By uniting these stakeholders, MSPs foster a synergistic environment for shared objectives, such as improved access to high-quality seeds, enhanced production and market dynamics, and greater farmer satisfaction regarding variety of characteristics in production and consumption [4]. Shared knowledge and best practices play a central role in stakeholder collaboration allowing participants to exchange effective postharvest management techniques including proper handling, storage and transport methods which significantly reduce losses [89] [9]. Resource optimization is another major benefit, as stakeholders can collectively leverage resources such as cold storage and efficient transportation essential for preserving perishable goods [2]. MSPs contribute directly to these resource efficiencies by facilitating access to improved bean varieties, reducing the age of farmed varieties and cutting travel time to seed markets for farmers [51]. The integration of technology further strengthens these collaborative efforts. Stakeholders can jointly invest in and adopt advanced technologies such as Geographic Information Systems (GIS) which optimize logistics and provide location-based recommendations for storage facilities, ultimately reducing postharvest losses [2] [39]. Additionally, collaborative initiatives often include training and capacity-building programs that equip farmers and handlers with modern postharvest techniques ensuring better handling and extending shelf life [9]. However, effective stakeholder collaboration faces challenges, particularly for small-scale producers including financial constraints and limited access to technology. Addressing these barriers is essential for maximizing stakeholder engagement's potential to reduce postharvest losses. Multi-stakeholder partnerships provide structured frameworks such as the sequential, integrated, sustainable organization-stakeholder relationship model which emphasizes strategic stakeholder identification, development, and maintenance to establish robust organizational-stakeholder alliances aimed at addressing postharvest issues in horticulture [91]. These structured approaches in MSPs exemplify how cross-sectoral cooperation can drive sustainable and resilient postharvest management in Indian horticulture.

Future direction and recommendation

Future trends and innovations in post-harvest utilization

The development of food processing efficiency and sustainability in the post-harvest use sector demands the adoption of future trends and innovations [52]. The processing and preservation of biofortified crops such as sweet potatoes and cassava are being revolutionized by technologies including safe packaging, continuous flow microwave systems, and flash-drying which ensure nutrient retention and a wide range of end-product applications [21]. Furthermore, when mixed with traditional processes, emerging technologies like nanotechnology, pulsed electric fields, and ultrasound treatments have shown encouraging outcomes in terms of decreased energy and water usage, shortened processing times, and enhanced product quality. Sustainable post-harvest techniques require cooperative efforts integrating genetic advancements, sensor technology, and creative packaging solutions, highlighting the importance of complete techniques from production to consumption.

Strategies to enhance post-harvest loss utilization and sustainability

In horticulture, multiple strategies are necessary to improve post-harvest loss utilization and sustainability. Advances in sensor technology to monitor ripeness and maturity as well as genetic advances in cultivars for flavor, texture and longer postharvest life are critical [21]. Modern genetic technologies such as genome editing (e.g., CRISPR/Cas9), can be used to improve post-harvest stability attributes in horticulture crops such as disease resistance and shelf life [49]. In order to preserve quality and lower the estimated 25–30 per-cent postharvest losses of fruits and vegetables rich sources of critical nutrients coordinated, methodical handling is needed [82]. Sustainable postharvest management techniques are essential for maintaining fresh produce's freshness and the environment and this includes innovative packaging methods that use biodegradable materials [56]. It is essential to take proactive steps that include every aspect from production to consumption.

Policies and initiatives for post-harvest management in horticulture in India

Different policies and schemes are designed to enhance the efficiency and sustainability of post-harvest management practices within India's horticulture sector as shown in figure 4. These initiatives aim to minimize post-harvest losses, thereby optimizing the supply chain and ensuring that produce retains its nutritional and market value from farm to consumer. By facilitating the development of advanced storage, processing, and transportation infrastructure, these measures significantly contribute to improved farmer income, product quality, and the overall profitability of horticultural operations. Moreover, the reduction of post-harvest losses plays a critical role in minimizing food waste, thereby contributing to national food security and environmental sustainability. These efforts are instrumental in creating a more resilient and efficient horticultural value chain, promoting both domestic market stability and export.

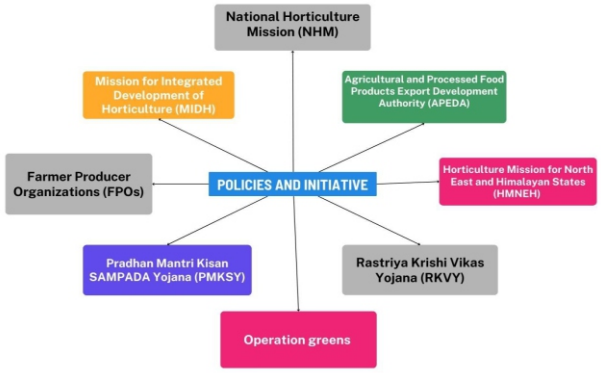

Fig .4.Policies and initiatives for post-harvest management in horticulture in India

National Horticulture Mission (NHM)

Launched in 2005-06, the National Horticulture Mission aims to promote the sustainable growth of the horticulture sector by boosting production, improving nutritional security, and providing income support to farmers. A key focus of this mission is the development of post-harvest management infrastructure, such as cold storage facilities and packhouses, which are essential to reducing losses and improving the quality of produce. These efforts play a vital role in ensuring that horticultural products reach markets in optimal condition, minimizing spoilage and wastage [72].

Mission for Integrated Development of Horticulture (MIDH)

Initiated in April 2014, this centrally sponsored scheme seeks to ensure the holistic development of the horticulture sector. The mission covers a wide range of horticultural crops and places particular emphasis on post-harvest management, processing, and marketing. The government extends substantial financial assistance under this scheme to support the creation of necessary post-harvest infrastructure, which includes the construction of cold storage units, pack houses and transportation facilities to preserve the quality of produce from farm to market [84].

Horticulture Mission for North East and Himalayan States (HMNEH)

A sub-scheme of MIDH, the Horticulture Mission for North East and Himalayan States is tailored to address the unique challenges faced by these regions. Launched to support horticulture in the northeastern and Himalayan areas, this initiative emphasizes the development of post-harvest infrastructure that suits the local environment and conditions. By focusing on region-specific needs, the mission helps to enhance efficiency, reduce losses, and improve market access for farmers in these often remote and challenging landscapes [54].

Farmer Producer Organizations (FPOs)

To enhance farmers' collective bargaining power, the government has promoted the formation of Farmer Producer Organizations (FPOs). These organizations enable farmers to access better training in post-harvest management practices, technology, and market opportunities. Through FPOs, small and marginal farmers can pool resources, increase their market presence, and leverage shared infrastructure, leading to better returns for their produce [55].

Pradhan Mantri Kisan SAMPADA Yojana (PMKSY)

Launched in 2017 by the Ministry of Food Processing Industries, the Pradhan Mantri Kisan SAMPADA Yojana (PMKSY) is a comprehensive scheme aimed at developing modern infrastructure in the food processing sector, including post-harvest management facilities. Under this scheme, financial assistance is provided for the establishment of cold chains, mega food parks and integrated processing units. The initiative aims to reduce agricultural waste, increase farmers' income and promote the export of processed food products, thereby enhancing value addition in the horticulture sector [79].

Rashtriya Krishi Vikas Yojana (RKVY)

The Rashtriya Krishi Vikas Yojana, launched in 2007, is a state-level initiative that encourages states to enhance their agricultural productivity, including horticulture, by implementing specific agricultural development plans. One of the key focus areas of RKVY is post-harvest management, which includes the construction of cold storage facilities, packhouses and processing units. The scheme provides funds to state governments for developing infrastructure to improve the value chain and reduce post-harvest losses [97].

Operation greens

Inspired by the success of Operation Flood, the government launched Operation Greens in 2018, with an initial focus on managing the supply chain for tomatoes, onions and potatoes. The scheme aims to stabilize prices for these perishable commodities by providing support for infrastructure development, including cold chains, storage facilities, and transportation. Over time, the scope of Operation Greens has expanded to cover more horticultural crops, addressing key challenges in post-harvest management and ensuring stable prices for both farmers and consumers [73].

Agricultural and Processed Food Products Export Development Authority (APEDA)

APEDA, established in 1985, plays a critical role in the promotion of agricultural exports, including horticultural produce. One of its mandates is to assist in the development of post-harvest infrastructure such as grading, packaging and processing units, to meet international quality standards. APEDA provides financial assistance for setting up cold storage, packhouses, and other infrastructure needed for maintaining the quality of export-bound horticultural products. This not only reduces post-harvest losses but also boosts India's horticultural exports [7].

Conclusion

Through a thorough evaluation of current literature, we have elucidated the critical role of post-harvest management in the sustainable utilization of surplus horticultural produce. This review emphasizes the necessity of optimizing post-harvest practices to minimize food losses, reduce greenhouse gas emissions and enhance resource efficiency within the agricultural sector. Surplus horticultural produce, when not appropriately managed, contributes to substantial environmental degradation, including unnecessary depletion of resources and ecosystem damage. We propose a systemic approach that integrates advanced post-harvest technologies, efficient logistics, and circular economy principles to address these challenges. The adoption of innovative practices in storage, processing, packaging, and distribution can

significantly mitigate losses and environmental impacts while simultaneously improving food security. Furthermore, surplus horticultural produce can be redirected for a variety of sustainable applications, such as composting, biogas production, and value-added food processing, thus contributing to waste minimization and the creation of alternative revenue streams. These approaches not only enhance food security but also reduce the environmental footprint of surplus produce, which often leads to wasted resources and increased emissions in landfills. Surplus production, if effectively managed, presents a significant opportunity to reduce food waste and optimize the utilization of horticultural outputs. This involves leveraging underutilized or excess produce through innovations in preservation and processing technologies, improving supply chain efficiencies and exploring secondary market opportunities for non-standard or excess produce. Such strategies can help balance production and consumption while minimizing environmental impacts. The involvement of key stakeholders including farmers, agribusinesses, policymakers and consumers is essential for the effective implementation and scaling of these practices. Collaborative action across sectors is necessary to develop and enforce policies, standards and incentives that support sustainable post-harvest management and the utilization of surplus produce. By aligning post-harvest strategies with global sustainability goals, the agricultural sector can contribute to mitigating climate change, enhancing biodiversity and promoting the long-term ecological health of the planet. This review calls for a paradigm shift in post-harvest management practices, advocating for a systems-based approach that ensures surplus horticultural produce is utilized in a manner that supports both environmental and socio-economic sustainability.

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