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Emerging Trends in Fruit and Vegetable Science: Advances in Cultivation, Postharvest Management, and Value Addition

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Abstract

Fruit and vegetable industries are undergoing a radical restructuring as a result of technological development, sustained focus on sustainable development, and rising customer preferences. This review focuses on the latest changes and developments in cultivation, postharvest, value-addition, and management in the global landscape of horticulture. With a global cultivation of 367.72 million tons and a combined market value of greater than 800 billion USD, the sector grapples with significant challenges; as much as 40% postharvest losses, climate change, and the need for sustainable intensification. This review focuses on trends, such as: precision and smart agriculture, controlled environment agriculture (CEA), use of artificial intelligence, postharvest innovations, and new approaches in value-addition technologies. This review also focuses on innovations, such as vertical farming, hydroponics, and the use of nanotechnology for edible coatings, pulsed electric field, and circular bio-economy. The result of the review has been organized in the form of five detailed tables that represent the comparative analysis of cultivation systems, postharvest technologies, preservation, value-addition, and quality control systems. The synthesis shows that primary postharvest losses can be addressed through some optimally integrated technologies. Repeating this process can also yield better results with how reservations and resources are used, be more time-efficient, and cost-efficient, with a 70–98% efficiency. They can also make products more marketable through extended shelf-lives, whereby shelf lives can be extended by 50–300%. Future research on this emerging field can provide greater clarity for practitioners and policy makers on the road to achieving greater evidence-based synergies for sustainable intensification in the vegetable and fruit sector of the economy, with an increased focus on the intersection of digital technologies, the latest biotechnologies, and principles of the circular economy as the cornerstone of future systems in the fruit and vegetable sector of the economy.

Keywords: Artificial intelligence, nanotechnology, postharvest technologies, precision agriculture, sustainable horticulture, value addition

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INTRODUCTION

Context and Significance

The horticulture industry has expanded from 280.70 million tons in 2013–2014 to 367.72 million tons in 2024–2025, leading to a 31% increase in market value to about 800 billion USD. The CAGR for the industry is approximately 5% with increasing health, urbanization, and income, with the most growth observed in the Asia-Pacific and Latin American countries. This sector has also seen growth in the demand for fruits and vegetables which are essential for a balanced diet [1–5]. The sector is also currently experiencing a lot of challenges. According to various studies, postharvest losses in fruits and vegetables in developing countries have been estimated to be between 25–40%, while losses in developed countries are estimated to be between 5–10%. This results in a large amount of wasted economic and nutritional resources. Losses occur due to inadequate postharvest infrastructure, poor cold chain logistics, and damage caused by the decomposition of the fruits and vegetables, as well as the spoiling of the products, and damage caused by the fruits and vegetables during handling and transport. Climate change is contributing to the challenges mentioned by increasing temperature variability, changes in precipitation, and more pests and diseases.

Convergence and Innovation Drivers

The modern fruit and vegetable industry is the result of several technological advancements. The Fourth Industrial Revolution is one of the major innovations and consists of digitalization, automation, and the use of data in decision-making. The Fourth Industrial Revolution is revolutionizing the entire industry. Advances in other industries, such as biotechnology, nanotechnology, and materials science, provide more efficient and effective methods of growing, maintaining, and transforming food. The need to maintain the environment opens a new area for developing innovations and proposes using resources more efficiently and the safe handling of waste [6–8]. The rapid change in the marketplace has been seen in consumer demand for organic options, locally grown food, and ready-to-eat food. The demand for food to be grown and processed in a sustainable manner has increased. The need for food to be safe to eat has created a demand in the marketplace. Using policies that promote sustainable food and agricultural practices, this has created a need for using technology and innovation [9–11].

Review Scope and Structure

This review will focus on the emerging practices in the three critical areas of the fruit and vegetables of the value chain. The review will cover three areas: Frequency of value chain analysis in the fruit and vegetable sector, frequency of use of value chain practices of fruit and vegetable vertical integration, and integration of chain control methods, such as precision farming and controlled growing environments. The review will also cover new and emerging practices in managing fruits and vegetables to keep and improve their quality, and the new and emerging practices that will improve and change the quality of the products [12–15].The review integrates recent academic publications, industry publications, and technology assessments from 2021–2026, focusing on technologies that are commercially viable or exhibit high potential for research advancement.

DEVELOPMENT OF CULTIVATION TECHNOLOGY

Advancement of Cultivation Technology

The shift from the practice of treating a field as a uniform unit, and towards the practice of engaging a field as a dynamic system that requires different inputs at different times and places, is called precision agriculture. The use of IoT sensors, remote sensing, GPS, and AI, encourages a shift towards a more data-driven approach that focuses on the optimization of inputs and enhanced productivity using techniques, such as data-driven cultivation [16–18].

Sensor and Data Acquisition Technology

The horticulture industry employs the use of multi-sensor networks that monitor various data points including soil moisture, temperature, humidity, and nutrient levels, as well as, indicators of plant health and microclimates [19]. The data streams generated by these sensors support precision irrigation, variable-rate fertigation, and pest control management. The collaboration of soil moisture sensors and forecasting weather algorithms optimizes the irrigation schedule, allowing for a 30–50% improved water saving without compromising yield. The use of remote sensing technologies and satellite imagery, unmanned aerial vehicles (UAVs or drones), and hyperspectral ground-based cameras facilitate the non-invasive remote (spatially extensive) observation of crop health [19]. Before the visual symptoms of plant stress, nutrient deficiencies, disease symptoms, and pest infestations, hyperspectral, and multispectral imaging allows for the observation of the stimuli, and thus, early intervention strategies [19].

Technologies of Sensing and Acquiring Data

The use of various sensor networks in modern horticultural operations to monitor soil moisture and temperature, humidity, nutrients, plant health, and microclimatic conditions is becoming more and more common [20]. These sensors stream continuous data for the purposes of precision irrigation, variable-rate fertilization, and pest control actions when needed. Using soil moisture sensors and weather forecasts, irrigation is optimized and can save water by 30–50% while still maintaining or improving crop yields. Riverside Technologies estimates up to 50% crop yield improvement and 30–50% water savings with the right predictive analytics paired with soil moisture sensor data.

Artificial Intelligence and Decision Support System

Out of the various AI algorithms, the most beneficial for the purposes of sensor data analysis are machine learning and deep learning models [3,8]. These models offer greater than 95% accuracy for the computer-vision-based automatic detection and classification of plant diseases, pest population counts, and fruit maturity assessments [21]. Predictive models are being used for the detection of plant diseases, real-time optimization of harvest time, as well as yield estimation and optimization. In India, AI-driven precision farming programs use ground sensors, satellite images, and GPS to give farmers individualized suggestions on irrigation, fertilizer application, and pest control. These systems could increase efficiency in the use of various resources by 20–35%, and increase productivity by 10–25%. AI in combination with automated machines can do autonomous activities, such as, operational costing, labor costing, and targeted spraying [19, 20] seeding and selective harvesting.

Vertical Farming and Controlled Environment Agriculture

Controlled Environment Agriculture (CEA) is an innovative method for growing crops. This method is growing crops while maintaining the right amount of each growing factor (light, temperature, humidity, CO_2, and nutrients) regardless of outside environmental factors [21].

Vertical Farming Systems

Vertical farming refers to growing crops in layers vertically while also incorporating a controlled environment and usually a soil-less growing system. This method of farming spatially optimizes the land and increases production by 10 to 20 times compared to traditional field production [22, 23]. Commercial vertical farms grow crops like lettuce, herbs, strawberries, and tomatoes with a volume of production 100 to 400 times compared to traditional farms [24].

Soilless Cultivation Methods

Vertical farming primarily uses three soilless systems:

Hydroponics is a method of growing plants in which the roots are submerged in water mixed with nutrients. There are many types, including: nutrient film technique (NFT), deep water culture (DWC), and ebb-and-flow. Hydroponics systems take 70–90% less water than soil-based systems in growing plants, as they continuously recirculate the nutrient water solution [25].

In aeroponics, plant roots are suspended in the air and nutrients are delivered to the roots via a fine mist. Aeroponics is also a system that requires very little water; in fact, it uses 90% less than hydroponics and because of this, the plants grow much quicker and are nutritionally denser. While this system greatly improves and accelerates the retrieval of nutrients and oxygen, it is less used than hydroponics because it is more technically complicated [26].

An example of a circular economy system is called aquaponics, and this system combines hydroponics and aquaculture (the farming of fish). In this system (in Table 1), the nutrient supply for the plants is the waste of the fish and the plants purify the water, which is then recirculated to the fish tanks. This system is more complex than the other systems due to biological complexities and also requires more management complexity [21].

Sustainability and Resource Efficiency

With CEA systems, there are amazing metrics for the efficiency with the following:

- *Water:* 70–98% less than in-field production water consumption due to recirculation and less water lost to evapotranspiration [21, 29]
- *Land:* 10–400 times higher productivity per unit area [24, 29]
- *Pesticides:* None. In a controlled environment, disease, and pests that encourage the use of pesticides are not present [21]
- *Production:* Uninterrupted seasons means continuous harvesting which is the most efficient use of the facility and the most supply for the market [24]
- *Urban Proximity:* Locating production sites close to sites of consumption (proximal production) can decrease transport emissions and food miles by 50–90% [5].

Despite significant promise, CEA is constrained by several factors, including a very high initial capital investment (USD 1,000–3,000 per square meter), high energy intensity (especially for lighting and climate control), need for a high level of technical proficiency, and limited suitability for crops other than high-value leafy greens and herbs [27]. Current research aims to broaden the range of crops that can be grown, improve the energy balance of CEA systems through using renewable energy, and decrease initial capital investments through using modular systems and greater levels of automation.

POSTHARVEST MANAGEMENT INNOVATIONS

Non-Thermal Processing Technologies

Postharvest losses are a major concern because 25–40% of harvested fruits and vegetables are lost before they are consumed [3, 12]. Traditional thermal processing method gets rid of microorganisms and enzymes, but it also destroys some of the heat-sensitive nutrients and alters the sensory characteristics of the food. In addition, it increases the cost of processing. Some non-thermal methods, however, maintain the nutrients and sensory characteristics of the food while also extending the shelf life and ensuring that the food is safe to eat as shown in Table 2.

Pulsed Electric Field (PEF) Technology

PEF treatment involves the application of short (microsecond to millisecond) and high-voltage electrical pulses to food, causing the formation of temporary pores in the membranes of microbes (electroporation) and ultimately leading to cell death. This occurs without a significant increase in temperature [6, 9]. PEF treatment also preserves heat-sensitive nutrients, such as vitamin C and some of the anthocyanins and phenolic compounds. Other PEF treatment applications include microbial reduction in fresh cut fruits and vegetables, enzyme inactivation to prevent browning, enhanced extraction of bioactive compounds from the tissues of plants, and improved drying efficiency through tissue softening [9]. PEF treatment maintains the fresh-like quality attributes of fresh-cut produce, resulting in a shelf life extension of 3–7 days.

High Hydrostatic Pressure (HPP) Processing

HPP processing involves subjecting packaged food to 400–600 MPa pressure, resulting in the inactivation of microorganisms and enzymes due to the denaturation of proteins. This process does not have a significant impact on the small molecules that are responsible for the flavor, color, and nutrition of the food [6, 9]. Compared to thermal processing, HPP-processed food retains 90–100% of its original vitamin content, while thermal processing retains only 50–70% of the original vitamin content. Some examples of commercially HPP-processed foods are fruit juices, smoothies, guacamole, salsa, and ready-to-eat vegetable products. Integrating High pressure processing (HPP) into the supply chain offers the benefit of extending the refrigerated shelf life of food from 7–10 days to 30–45 days without using preservatives, resulting in the ability to keep food in pantry for longer periods of time, minimizing waste, and extending the geographic reach of the product distribution. The use of HPP, however, is limited due to the great expense of the processing machinery (typically $1–2 million dollars), as well as the batch processing capabilities that only allow the HPP of high margin food products.

Table 1. Comparative analysis of cultivation technologies for fruits and vegetables.

Cultivation System	Water Use Efficiency	Land Productivity	Key Advantages	Main Limitations
Conventional Field	Baseline (100%)	Baseline (1x)	Low capital cost, proven technology, diverse crops	Weather dependent, high water use, pesticide needs
Precision Agriculture	30-50% reduction	10-25% increase	Optimized inputs, reduced waste, scalable	Requires technology investment, technical expertise
Hydroponics	70-90% reduction	10-20x increase	Water efficient, controlled quality, no soil needed	High initial cost, limited crop range, technical skills
Vertical Farming	90-98% reduction	100-400x increase	Space efficient, urban integration, year-round	Very high capital cost, energy intensive, crop limitations
Aeroponics	95% reduction	15-25x increase	Maximum efficiency, rapid growth, high nutrition	Complex systems, high maintenance, limited adoption

Table 2. Advanced postharvest technologies for fruit and vegetable preservation.

Technology	Mechanism	Shelf life extension	Quality preservation	Commercial status
Pulsed Electric Field	Electroporation of microbes	3-7 days	Excellent nutrient retention	Emerging commercial
High Pressure Processing	Pressure inactivation	30-45 days (juices)	90-100% vitamin retention	Established commercial
Cold Plasma	Reactive species	2-5 log microbial reduction	Minimal quality impact	Research/pilot scale
Nanocoatings	Enhanced barrier properties	14-21 days extension	Superior moisture/gas barrier	Advanced research
Modified Atmosphere Packaging	Gas composition control	50-200% extension	Good quality maintenance	Widely commercial
Controlled Atmosphere Storage	Precise environmental control	300-400% extension	Excellent long-term storage	Established commercial

Advanced Coating and Packaging Technologies

Nanotechnology-Enhanced Edible Coatings

Edible coatings applied to food products appear to act as a barrier independently from the materials that comprise the edible coatings. The materials that are used to create the edible coatings create an atmosphere that slows the respiration rates of food, and traps moistures and inhibits the growth of organisms that are used to create and/or enhance the coatings. The materials that are used in the creation of the coatings are used to create and/or enhance the coatings. The use of enhanced antimicrobial activities and the use of enhanced antimicrobial activities. The use of enhanced barrier properties of the coatings and/or the use of enhanced barrier properties of the coatings and/or the use of enhanced antimicrobial activities have been researched extensively and are presently under investigation regarding the existences of the coatings that are present. Compared to regular coatings, nanocoatings show improved water vapor barrier (30–50% improvement), improved oxygen barrier (40–60% improvement), and improved mechanical properties. Nanoemulsion coatings, unlike regular emulsion-based coatings, offer improved adhesion and optical properties while retaining the original appearance of the coated product [30]. Incorporating antimicrobial and antioxidant agents (essential oils, plant extracts, antimicrobial peptides) into nanocoatings enables the nanosystem to control the release of active agents over the storage period. This maintenance of effective concentrations, while preventing initial toxicity and subsequent rapid loss dispersion, is a strategy to preserve the efficacy of the antimicrobial agents during the storage period [22, 28]. Pears covered with chitosan-cellulose nanocrystal coatings (test) were extended to 14–21 days compared to 7–10 days for uncoated pears, while preserving the firmness, acidity, and sensory quality [28].

Research has focused on the need for thorough safety evaluations of nanomaterials in food, the tailoring of specific formulations to particular food commodities, the low-cost scaling of formulations for specific foods, and the creation of regulatory processes to control the commercialization of nanocoating [25].

Active and Intelligent Packaging

Active packaging systems include components that purposely interact with the product or the headspace gas to prolong the storage time of the product. This includes oxygen scavengers, ethylene absorbers, moisture control, antimicrobial release, and CO_2 release/absorption [9, 12]. MAP (modified atmosphere packaging) provides gas control in the packaging of food to reduce O_2 gas and increase CO_2 gas, slowing down the respiration and senescence of the food and the microbial spoilage.

Sensors and indicators that provide real-time information regarding the status of the product contained in the packaging are examples of intelligent packaging. TTIs (time and temperature indicators) provide a record of the temperature history of the food and alert the consumer to a breach of the cold chain.

Freshness indicators identify CO_2, amines, and organic acids which indicate the begining of spoilage. Gas sensor technology allows to measure the composition of the gases present in the packaging [6, 9].

When active and intelligent features are integrated with materials that are biodegradable and compostable, the negative impact of plastic packaging can be mitigated. Polylactic acid (PLA), polyhydroxyalkanoates (PHA) and some cellulose-based films can be used as barriers when modified with nanofillers, and are ecofriendly alternatives [12].

Storage and Cold Chain Optimization

Controlled and Modified Atmosphere Storage

Controlled Atmosphere (CA) storage allows for precise control of the storage environment by regulation of the oxygen, carbon dioxide, temperature, and humidity of the storage which can extend the length of time the produce can be stored [9, 12]. The ideal environment for storage of each type of produce must be determined individually. For instance, storage of apples in a controlled environment with temperature between 0 and 4 degrees Celsius, 1–3% levels of O_2 and 1–5% levels of CO_2 can extend the storage time to 8–12 months, in comparison to 2–4 months with typical cold storage.

Dynamic CA Systems can use real-time data of the respiration and ethylene production of the stored produce to adjust the composition of the atmosphere as required. Changes to the stored produce's physiology throughout the storage period allow the system to respond. Compared to traditional CA storage, this system is designed to reduce the occurrence of storage disorders and the degradation of the quality of the stored produce [12].

IoT-Enabled Cold Chain Management

Today's sensors allow for the combination of the Internet of Things (IoT), wireless technology, cloud computing, and data processing which allows the cold chain to become more than just the maintenance of cold temperatures; the system can maintain and optimize the quality of the items being stored [12]. In every stage of the cold chain, sensors measure temperature, humidity, and gas composition, and the sensors can keep track of these parameters continuously.

Data in motion enables quality prediction modeling, pathway optimization, and real-time responses through corrective action when specific thresholds are surpassed.

The supply chain directly connects farm and consumer, and uses blockchain technology to improve supply chain accountability and traceability at all levels through using blockchain to secure an unchangeable record of all transactions at each supply chain level. This record can help to improve

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supply chain fungibility, transparency, and better traceability to the consumer. Provide better consumer confidence, improve supply chain recall and reduce supply chain quality decay through the entire supply chain.

Energy-Efficient Storage Technologies

Integrating Phase Change Materials (PCM) into transport and storage containers also improves PCM temperature stability and improves PCM energy savings (20–40%) through better temperature control. PCM can stabilize temperatures through their ability to store and release heat energy through their phase change. This reduces cooling and enhances temperature control through PCM cooling.

Remote refrigeration technology using solar energy can improve postharvest loss around the world, especially in locations with no power, and no refrigeration. Improving off the grid postharvest losses through solar energy remote refrigeration. Off the grid solar energy remote refrigeration reduces postharvest losses using hybrid solar, grid, and back-up power at a 30 to 60 percent reduction in operational costs.

ADVANCES IN FOOD PRESERVATION

Pressure Processing for Juices

In the premium juice and smoothie category, HPP (High Pressure Processing also referred to as cold pasteurization as it delivers 5 log microbial reduction and retains the fresh, vibrant color and the heat sensitive nutrients) dominates the market with over 500 commercial units processed in the world and worth 8 billion dollars.

HPP juice prices are 40–80% more than thermally processed products, and its sensory quality and nutritional attributes are appealing to health-conscious consumers. Consumer awareness and market growth of 12–15% is a result of more consumers expanding the distribution of specialty retailers into HPP juice and smoothies.

Freeze-drying and vacuum processes. Freeze drying, or lyophilization, is a drying technique where 90–95% of the nutrients are preserved, and the colors (of the fruits and vegetables) are kept intact. In addition, the cellular structure of the dried fruits and vegetables is kept, so they can be rehydrated quickly and easily with texture recovery [10]. This technique can be used for dried fruit pieces used in cereal and snack products, vegetables used in instant soup products, and other functional foods.

The technique is also very expensive, with the initial capital cost of an individual unit being 500,000–2 million dollars. In addition, the operational costs (per kg of product) are 3–8 dollars. Because of this, freeze drying is limited mainly to high value uses, such as organic baby food, nutritional supplements, and special ingredients [10]. Uses that are less expensive, and also require using lower temperatures, are vacuum drying, which is also less than traditional dehydration and provides intermediate quality and cost between traditional (air) drying and freeze drying.

Extraction of Bioactive Compounds and Functional Ingredients

Circular Bioeconomy Strategies

The food and vegetable industry generates 25–30% by-products, such as peels, seeds, pomace, and trimmings. This is not only a problem for the environment but also a great opportunity as these by-products are often valuable and contain useful bioactive compounds (antioxidants, polyphenols, carotenoids, vitamin C) dietary fiber, and more [11, 12].

Different bioactive compounds can also be valuable as they can be used in ways that can improve the nutritional value, shelf life, and quality (antioxidants) of the processed foods. These bioactive compounds can be valuable as the raw materials also have bioactive components and the raw materials that are used as the by-products have bioactive components, which include the following:

- Obtaining natural colorants that can be used in place of synthetic colorants in food and cosmetic products, such as anthocyanin extracted from berry waste and carotenoids that derived from tomato pomace.
- Recovering and using bioactive compounds as natural antioxidants that extend the durability of processed foods to also improve the nutritional value of processed foods [10–12].

Extraction methods that can be used to recover bioactive from waste streams of various extraction techniques include:

- Ultrasound-assisted extraction (UAE),
- Microwave-assisted extraction (MAE),
- Supercritical fluid extraction (SFE), and
- Enzyme-assisted extraction (EAE).
- Concentrates made from dietary fiber boost the nutritional value and improve the texture of baked goods, dairy, and meat products.
- Functional components in nutraceuticals, dietary supplements, and cosmeceuticals

Citrus peel extracts that contain flavonoids help with inflammation and the cardiovascular system. Grape seed and pomace extracts that contain proanthocyanidins have strong anti-cancer properties and help with oxidation. Tomato by-products contain lycopene which is a carotenoid and can help lower the risk of prostate cancer [12, 15].

Fermentation and Biotransformation

Technologies using fermentation can upgrade the nutritional, functional, and sensory properties of fruits and vegetables to make value-added products. Fermented probiotic vegetable drinks use the bioactive metabolites from fermentation and live/probiotic cultures to meet the demand for functional drinks [11–13]. Solid-state fermentation using fruit and vegetable waste can produce food and feed enzymes (cellulase, pectinase, and amylase) and organic acids (citric and lactic) and microbial proteins. Biotransformation is using a specific microbial strain or enzymes to change parent compounds to forms that are more bioavailable or bioactive. This is seen with the change of phenolic glycosides to free aglycones that have a higher importance in antioxidant properties.

Novel Product Development

Plant-Based Meat and Dairy Alternatives

The revolution in plant-based foods has created multiple possibilities for using vegetable-based ingredients. The proteins found in peas, beans, and other legumes can create textured matrices that mimic the structure of meat. Additionally, vegetable extracts can be added for color (like beetroot juice), flavor, and nutritional fortification in plant-based foods.

Market growth for all plant-based categories now exceeds $30 billion, growing 15–20% annually due to health, sustainability, and ethical concerns. Vegetables perform more supportive and versatile roles, providing micronutrients, fiber, vitamins, minerals, and bioactive compounds as supporting nutrients to the primary proteins of legumes and grains.

Functional Beverages and Shots

Processed health products, such as cold-pressed juice, smoothie shots, and functional veggie drinks target the health-conscious consumer. Formulations are more expensive because they target specific health goals like immunity support from vitamin C rich citrus and cruciferous vegetables, digestion support from prebiotic and fermented vegetable fibers, detox from chlorophyll-rich greens, and energy from nitrates in beets.

Due to their organic certifications, cold-chain distribution, and minimal processing, premium prices ($4–8 per serving vs $1–2 for standard juices) are supported. Premium priced health products are also available in health food stores, fitness centers, and specialty retailers.

Powered and Concentrated Ingredients

Several processes, including spray drying, freeze drying, and vacuum concentrating, are used to make fresh produce shelf stable and powdered. These vegetable powders provide natural color, such as from spinach, beetroot, and turmeric, functional, and nutritional benefits, and can enhance products without changing texture or requiring reformulations.

In Table 3, The global market for fruit and vegetable powders is over $20 billion, growing at an annual rate of 8 to 10% for clean-label reformulation, natural color, and nutritional fortification. The Market report says that recently developed technologies that minimize thermal exposure and oxidation allow for the preservation of heat sensitive nutrients and the prevention of browning, which helps to preserve the quality of the powder throughout the storage period.

EMERGING TECHNOLOGIES AND FUTURE DIRECTIONS

Artificial Intelligence and Machine Learning Applications

In Table 4 shows that Post-harvest AI integration and post-harvest management_ AI integration transcends precision agriculture and encompasses post-harvest management, optimization of processing, and supply chain management. Machine learning models predict the best time to harvest while maximizing yields and quality by identifying and analyzing harvest weather conditions, growing degree days, and historical quality datasets [16]. In storage, integration of AI with models of quality to predict shelf life and the best time to market is possible by using the sensors data (temperature, humidity, ethylene, and volatile compounds).

In operational processing, AI analyzes the raw materials and optimizes yield and quality variability of the final products by optimizing each of the processing parameters (time, temperature, and pressure)

Table 3. Value addition technologies and market growth trends in fruit and vegetable processing.

Value addition strategy	Key technologies	Products	Market growth rate
Minimal Processing	Sanitization, MAP, edible coatings	Fresh-cut, ready-to-eat salads	6-8% annually
HPP Products	High pressure processing	Premium juices, smoothies, dips	12-15% annually
Freeze-Dried Products	Lyophilization	Fruit pieces, instant ingredients	8-10% annually
Bioactive Extracts	UAE, MAE, SFE from waste	Natural colorants, antioxidants	10-12% annually
Fermented Products	Probiotic fermentation	Functional beverages, pickles	15-18% annually
Powdered Ingredients	Spray/freeze drying	Vegetable powders, concentrates	8-10% annually
Plant-Based Alternatives	Texturization, fortification	Meat/dairy alternatives	15-20% annually

Table 4. Emerging technologies in fruit and vegetable systems - applications and development status.

Emerging technology	Applications	Potential benefits	Development stage
Artificial Intelligence	Harvest prediction, quality monitoring, optimization	20-35% efficiency gains	Commercial adoption
Blockchain Traceability	Supply chain transparency, safety, verification	Enhanced trust, rapid recalls	Pilot/emerging commercial
CRISPR Gene Editing	Shelf life extension, nutrition, stress tolerance	15-25% loss reduction	Research/regulatory review
Harvesting Robots	Selective harvesting, continuous operation	30-50% labor cost reduction	Advanced prototypes
Mobile Processing Units	On-farm processing, reduced transport	Minimize spoilage, local value	Pilot demonstrations
Biodegradable Packaging	Sustainable materials, reduced plastic waste	70-90% plastic reduction	Early commercial
E-Nose Quality Monitoring	Non-invasive freshness, shelf life prediction	Real-time quality management	Research/pilot scale

for each batch [3]. Real-time computer vision systems examine the product and adjust the equipment and removes the nonconforming products per the in the processing set.

In the supply chain, AI analyzes the production, storage, processing, and distribution activities of the different players, optimizing the inventory, providing the best route for the transport and defining the market to minimize the wastage and profitability maximizing [8]. The production is planned by avoiding production excess and stock depletion.

Blockchain and Traceability Systems

Immutable distributed ledger systems have addressed the verification of food safety, authenticity, and sustainability by recording each step of the supply chain and the movement of the products between different hands [2]. Each transaction (harvesting, processing, storing, transporting, and retailing) creates records within a timeframe and attached to the product to give complete traceability from the farm to the consumers.

This technology has many applications, including traceability, fast identification of contamination sources for targeted recalls rather than recalls of a whole category of products, and verification of organic certificates, geographical origin claims, and transparency regarding the environmental footprint and the fair labor abuse.

Consumers can find detailed information about the products they are purchasing by scanning the QR code on the packaging. This includes where the farm is located, the harvest date, the name and address of the processing facility, any quality certifications the product has, and how the product was handled and transported [2].

When looking at the integration of the Internet of Things (IoT), the automated capturing of data from the sensors can help remove the need for manual record-keeping and the problems of fraud. When smart contracts are in play, they will help capture agreements at a given time, which will simplify the process of making sure farmers and suppliers are paid.

Biotechnology and Genetic Improvement

The CRISPR-Cas9 tool has the unique ability to do targeted alterations to the genetic material of an organism. This can be done on specific and selected traits of an organism in a precise manner, and will help circumvent the GMO issues and complexities in some jurisdictions. This can be accomplished by regulating the rate of harvest for several crops, thereby improving the quality and useful life of the product. This also includes better disease resistance and a reduction in the amount of pesticides used [30].

The postharvest loss of tomatoes can be diminished by 15–25% due to the production of ethylene gas which triggers ripening, and the lettuce will be in the range of 2 to 3 times the vitamin C level normally found in a balanced diet. Additionally, there will be an improvement in the quality of freshly cut potatoes due to the reduction of browning, which will also eliminate the need for sulfite treatments [4].

The various pathways that can be used to adopt biotechnology are influenced by the acceptance of the public, the associated regulations, and the ideas of intellectual property. Building trust in adopting biotechnology can be done by emphasizing the positive impacts, such as better nutrition, reduced impact on the environment, and improved availability of food.

Policy and Regulatory Considerations

Supportive policies, such as dedicated R&D funding, infrastructure spending, tax policies, and positive regulations (especially novel policies regarding gene-editing, nanotech, and novel processing methods) promote the rapid adoption of technology [7,12].

The regulations regarding food safety must manage and assess risk, while also encouraging innovation, and address the scientific assessments of the risk of emerging technologies. International standards harmonization offers reduced trade barriers and facilitates technology transfer and market access [12].

Sustainability incentives (such as carbon pricing, regulations around using water, and reducing waste) create an economic rationale for the adoption of resource-efficient technologies. Public procurement of goods produced sustainably also fosters demand for such goods and, thereby, offers a justification for higher prices and increased adoption [7].

CHALLENGES AND BARRIERS TO ADOPTION

Economic and Infrastructure Constraints

High capital investments are needed for emerging technologies that create a major barrier to small producers and processors in developing areas. For example, precision farming tools, advanced processing technologies, and cold chain systems that are vital for the integrated processing and marketing of agricultural products, require investments in the range of thousands to millions of dollars. Economic viability also requires relatively high prices, reasonably high production efficiencies, or significant reductions in production losses to outweigh the investment, operating costs, and maintenance costs [24, 27]. Infrastructure deficits, such as unreliable power, limited cold chain systems, inadequate transport networks, and limited access to markets, despite the large net potential benefit, represent a disincentive to developing areas embracing advances in other the technologies.

Technical and Knowledge Gaps

Technologies require a considerable degree of sophisticated technical skill to operate that are often well out of the range of applicable skills within the current agricultural workforce. While training, extension, and decision support systems can help to fill the gaps, they also require high maintenance and significant infrequent stakeholder involvement [7, 18]. Data interoperability, system integration, and technology cohesion are essential for achieving distributed system optimization. The absence of seamless digital ecosystems leads to suboptimal system performance. Propriety systems, siloed data, and closed ecosystems are significant obstacles to achieving integrated system optimization [8]. Research is required to facilitate the customization of technology for a variety of crops across diverse and culturally sensitive growing situations. The lack of such research constrains a technology's adaptability and utility to the innovative potential of the technology within the parameters defined in the original line of development. The need for lasting investments in research and collaborative efforts among multiple stakeholders to expand technological portfolios is evident [18].

CONCLUSIONS AND FUTURE OUTLOOK

The use of Precision farming and systems that provide a controlled environment for growing crops is a promising way for improving efficient use of resources toward increased productivity and improvement of quality of crops. Technologies that operate year-round and allow production that is independent from climate constraints, combined with land productivity increases of 10–400% and water use reductions of 70–98% make these technologies relevant to the future of food systems, particularly in water scarce and land constrained situations, Continued improvements in energy use, cost, and the range of crops will determine the future of these systems. Modern advances in postharvest technologies, especially, of non-thermal processing, nanotechnology-based coatings, smart packaging, and IoT in cold chain management, provide solutions to the 25–40% postharvest losses that are still an issue in the sector. Successful use of these technologies calls for a systems approach that combines several technologies, and tailors to specific value chain/context and commodity. Investments in these technologies are justified as postharvest losses and technology costs are offset by market value losses or value additions due to shelf life increases of 50% to 300% and quality retention greater than standard. Strategies for adding value, such as minimal processing, extraction of bioactive compounds from waste, and the creation of new products, provide economic and biohealth benefits to the population and address the new consumer trends for convenience, and sustainable solutions to health and waste management.

The market growth in premium waste bioactive products in the last 5 years, with 8–20% growth per year, reinforces the need for continuous innovation The circular bioeconomy with processing byproducts as valuable components is the systems approach to "waste" that is necessary for sustainable intensification. The waste bioactive Added value and convenience to the processing of postharvest waste not only to the health of bioactive components in the waste but also to the sustainability of the circular economy.

Transformed systems of horticulture are expected from new technologies, such as artificial intelligence, robotics, blockchain for traceability, and biotechnology. To realize this potential, it is necessary to overcome economic barriers via innovative financing and public-private partnerships, formulate regulations that balance safety and innovation, develop an educational and extension system that builds technical skills, and finally, engage value chain stakeholders in participatory development processes. The future of fruit and vegetable systems depends on smart combination of digital technology, advanced materials, biotechnology, and circular economy principles to construct resilient, efficient, and equitable value chains that provide nutritious, safe, and sustainably produced foods to an increasing global population. The continuing research, investment, collaboration, and policy advocacy will shape the speed and fairness of the transition, which will significantly influence the food security, environment sustainability and rural livelihoods around the globe.

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