



Recent Advancements and Innovations in Post-harvest Handling, Storage, and Technology for Vegetables: A Review

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ABSTRACT

In a broad sense, Vegetables are highly perishable and experience significant qualitative and quantitative losses after harvest. Advances in post-harvest handling and storage technologies have become critical interventions for maintaining quality, extending shelf life, and reducing waste. This review explores recent developments in post-harvest management, including precision harvesting tools, innovative storage solutions, and smart packaging technologies. It also examines the challenges, such as infrastructural deficiencies, and highlights future opportunities for creating more efficient and sustainable vegetable post-harvest systems. These innovations are vital for sustaining vegetable quality, improving food security, and enhancing economic viability. Recent developments in post-harvest handling and storage technologies have been crucial in addressing this issue by curing, drying, and grading, rapid cooling and refrigeration, Processing and value addition. Those innovations play crucial roles in sustaining vegetable quality and shelf life extension, thus aiding in the process of economic viability and food security. This paper examines recent trends in post-harvest management such as precision harvesting tools (such as controlled atmosphere storage, modified atmosphere packaging), cutting-edge storage systems, and smart packaging technologies. The article identifies potential areas for further research to optimize post-harvest systems worldwide.

Keywords: Post-harvest loss; smart packaging; and storage.

1. INTRODUCTION

Vegetables are the cornerstone for human nutrition; they represent an important source of vitamins, minerals, dietary fiber, and bioactive compounds (Septembre-Malaterre et al., 2018). Although high water content makes vegetables highly perishable such as spinach, palak and vulnerable to rapid deterioration during post-harvest, they are quite significant. Post-harvest losses in India are estimated to range from 14-36% in fruit and 10-25% in vegetable (Muthukumar and Selvakumar, 2013) is due to inefficient cold chains, and poor storage. Such losses can affect economic returns besides increasing food insecurity and waste of resources. Advances in post-harvest handling and storage technologies, including innovative harvesting tools, temperature management systems, and intelligent packaging, are critical for sustaining vegetable quality, minimizing losses, and ensuring a steady supply of fresh produce to meet global nutritional demands (Bisht & Singh, 2024). These technologies enhance sustainability by reducing waste and improving supply chain efficiency. Vegetables are very important constituents of a healthy diet, due to highly nutritive properties such as vitamins and minerals, dietary fiber, and various bioactive compounds with immense health advantages (Makule et al., 2022). However, their high moisture content makes them particularly susceptible to rapid deterioration means cause easy losses due to provide better environment for microorganism, so efficient post-harvest

management becomes indispensable (Elik et al., 2019).

Globally, post-harvest losses in vegetables are alarmingly high, often exceeding 30%, especially in developing regions that lack adequate infrastructure, cold storage facilities, and advanced logistics systems (Rutta, 2022). These losses lead to diminished economic returns for producers, increased food waste, and exacerbated food insecurity.

Advances in post-harvest technologies offer a bright solution to these problems. Some of the innovations include. Precision harvesting tools minimize physical damage and ensure optimal timing, thus maximizing the initial quality of the produce (Hayat et al., 2023). Cold chain technologies, such as refrigerated transport and controlled atmosphere storage, help maintain freshness and prolong shelf life (Deep et al., 2024). Intelligent packaging with antimicrobial coatings, ethylene absorbers, and sensors for real-time quality monitoring contribute to reduced spoilage and extended usability (Han et al., 2021).

These technologies are essential in maintaining the world's vegetable supply chain through ensuring fresh produce to accommodate the growing population with minimum side impacts on the environment. Additionally, the reduction of post-harvest losses will complement the sustainable development, particularly through improving resource use efficiency and reducing

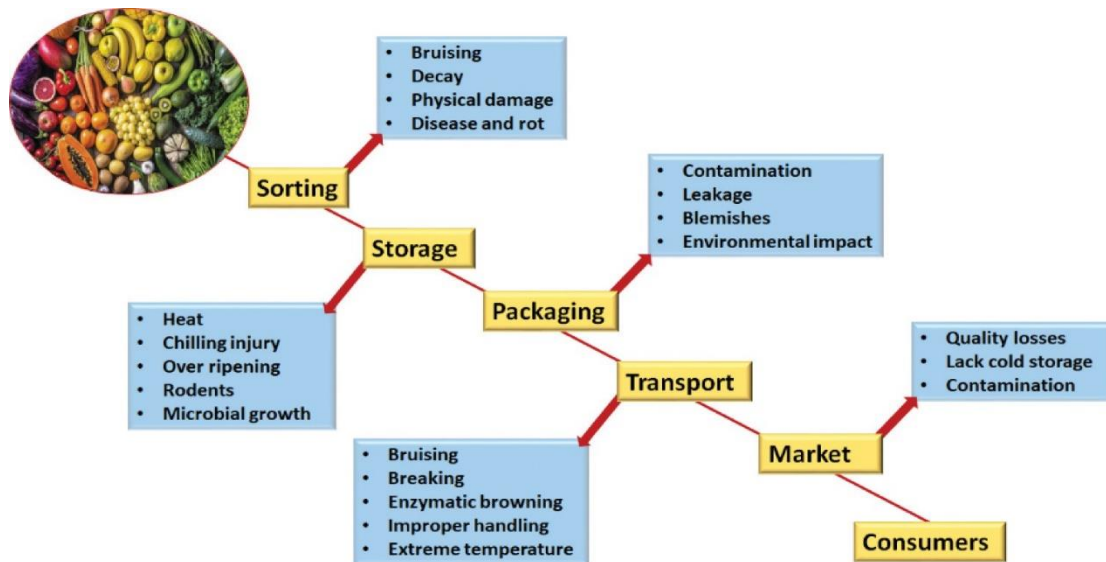


Fig. 1. Pictorial representation of post-harvest loss of crops at various stages from producers to consumers

(Source, Lalpekhlu et al., 2024)

carbon footprints (Van et al., 2017). Efforts in further enhancing the systems in post-harvest handling and storage can focus on: To develop low-cost and energy-efficient cold storage for small-scale farmers (Gouda et al., 2024). Stimulate the use of biodegradable, environment-friendly packaging material to minimize this impact (Jahangiri, et al., 2024). Invest in research and development for innovative post-harvest treatment methods such as edible coatings and advanced drying technologies (Jurić et al., 2024). Strengthen policy frameworks, public-private partnerships, and other institutions building infrastructure that leads to increased access to modern technology for post-harvest.

2. POST-HARVEST HANDLING TECHNIQUES

Post-harvest handling of vegetables involves a series of critical operations aimed at preserving quality, minimizing losses, and preparing produce for market or storage (El-Ramady et al., 2015). Recent advancements in technology have significantly improved these processes, offering more precision and efficiency.

2.1 Harvesting Technologies

2.1.1 Mechanized harvesting

Advanced precision harvesters now have built-in sensors and adjustable mechanisms that

minimize physical damage to the vegetables. They do not bruise or crush the vegetables (Rajapaksha et al., 2021). The machines are also highly automated, which means less labor is required.

2.1.2 Optimal harvest maturity

Non-destructive testing methods, such as near-infrared spectroscopy (NIRS), have revolutionized the determination of harvest readiness, providing real-time insights into parameters like sugar content, texture, and firmness, ensuring peak quality (Anjali et al., 2024). Innovations in determining the ideal harvest time using non-destructive testing methods, such as near-infrared spectroscopy (NIRS) (Goh et al., 2025).

2.2 Cleaning and Sorting

2.2.1 Automated sorting systems

High-speed automated systems, backed by artificial intelligence and machine vision technology, can detect imperfections and, based on this technology, sort vegetables according to size, shape, and color, taking out improperly grown or diseased produce with high accuracy (Kumar & Harsha 2024). High-speed sorting systems that employ artificial intelligence (AI), machine learning, and sophisticated robotics can automatically detect imperfections, classify by size, color, texture, and

ripeness, and pick out substandard volumes within a short span of time products for removal with excellent accuracy with uniformity, thus saving manpower (Nama, (Metcalf, 2019). This system can handle large 2022).

Table 1. List of different vegetable taken number of days from planting to market maturity under optimum growing conditions

Crop	Early variety	Common type	Late variety
Beans, bush	46	–	65
Beans, pole	56	–	72
Beans, lima, bush	65	–	78
Beets	50	–	80
Broccoli, sprouting ^a	70	–	150
Brussels sprouts ^b	90	–	100
Cabbage ^b	62	–	110
Carrots	60	–	85
Cauliflower, snowball type ^b	55	–	65
Chinese cabbage	70	–	80
Chives	–	90	–
Corn	70	–	100
Cucumber	60	–	70
Eggplant	70	–	85
Kohlrabi	55	–	65
Lettuce, head	60	–	85
Lettuce, leaf	40	–	50
Melon, Honey Ball	–	105	–
Melon, Honey Dew	–	115	–
Muskmelon	75	83	90
Mustard	40	–	60
Okra	50	–	60
Onions	85	–	120
Parsley	70	–	85
Parsnips	100	—	130
Peas	58	–	77
Pepper, sweet ^b	60	–	80
Potatoes	90	–	120
Pumpkin	110	–	120
Radishes	22	–	40
Radishes, winter type	50	–	60
Rutabagas	–	90	–
Spinach	40	–	50
Squash, winter	50	–	68
Squash, summer	80	–	120
Tomatoes ^b	65	–	100
Turnips	40	–	75
Watermelon	65	75	95

(Source, El-Ramady 2015)

Table 2. List of different vegetable and their maturity indices

Fruits/vegetables	Maturity indices or characteristics
Beans	Pods are filled, seeds immature
Broccoli	Adequate diameter, compact, all florets should be closed
Cabbage	Firm head
Cantaloupe	$\frac{3}{4}$ to full slip under slight pressure, abscission from vine
Carrot	Immature, roots reached adequate size
Cucumber	Immature and glossy skin
Garlic	Well filled bulbs, tops dry down
Ginger	8–9 months after planting
Melon	Ground color change to white with greenish tint, slightly waxy peel
Mushroom	Caps well rounded, partial veil completely intact
Okra	Pod 2–4" long, not fibrous, tips of pods pliable
Onion (dry bulbs)	When 10–20 % of tops fall over
Peas	Pods well filled but not faded in color
Pepper	Fruit size and color (depends on color and intended market)
Potatoes	Harvest before vines die completely, cure to heal surface wounds
Radish (spring)	20–30 days after planting
Radish (winter)	45–70 days after planting
Tomato	Seeds fully developed, gel formation advanced in at least one locule
Watermelon	Flesh color 75 % red, TSS = 10 %

(Source, El-Ramady, 2015)

2.2.2 Eco-friendly cleaning solutions

Biodegradable washing agents with antimicrobial properties have gained popularity, proving to be effective and sustainable to reduce microbial contamination without leaving residues (Gayathiri et al., 2022). Innovative techniques such as ultrasonic cleaning and ozone-based sanitation are also used to enhance safety and efficiency. The use of eco-friendly and biodegradable cleaning solutions that contain natural antimicrobial agents, such as essential oils and plant extracts, has increased the efficiency of microbial load reduction while preserving the organic nature of the vegetables (Lalpekhlua et al., 2024). Other techniques, such as ultrasonic cleaning, which dislodges dirt and contaminants using high-frequency sound waves, and ozone-based sanitation, which ensures effective disinfection without chemical residues, have also become popular for their sustainability and efficiency.

2.3 Handling and Transport

2.3.1 Cushioning Materials

Advances in cushioning materials such as biodegradable foams and reusable padding reduced mechanical damage when handling and transporting (Saengwong-ngam et al., 2024).

2.3.2 Refrigerated transport

Mobile refrigeration units with solar-powered backup systems have enhanced the transport of perishable vegetables, ensuring consistent temperature control even in remote regions (Amjad et al., 2023).

3. STORAGE TECHNOLOGIES

3.1 Modified and controlled atmosphere storage (MA/CA)

Oxygen, carbon dioxide, and humidity levels in the storage units are modified and controlled to slow down respiration rates, control microbial growth, and delay senescence of vegetables (Mangaraj & Goswami 2009). MA/CA systems are most efficient at extending shelf life for leafy greens, tomatoes, and root vegetables in regards to both nutrient retention and saleability (Yahia, 2019).

3.1.1 Energy-efficient refrigeration systems

Solar-powered refrigeration units and systems with enhanced insulation technologies have become a boon for remote and rural areas with unreliable electricity (Garcia et al., 2024). These systems use phase-change materials and energy-efficient compressors to maintain optimal storage conditions while minimizing energy consumption (Luerssen et al., 2020).

3.2 Innovative Storage Methods

New storage technologies have dramatically changed the concept of keeping vegetables, thereby providing them with an extended shelf life for freshness, nutrition, and commercial attractiveness (Verma & Joshi 2000). Scientific developments are put together with practical usage to ensure optimum storage conditions for different types of vegetables.

3.3 Hypobaric Storage

Hypobaric storage conditions have reduced atmospheric pressure, slowing the physiological activity of vegetables besides retarding ethylene production and microbial growth (Rao, 2015). This technique is suitable for high-value crops such as asparagus, broccoli, and peppers (Tyagi and Khire 2018). In these products, the requirements of maintaining fresh appearance and quality are of utmost importance in export markets and premium grades. This new technique maintains a reduced atmospheric storage condition that also reduces ethylene

production, diminishes microbial activities, and further enhances the shelf life of products like broccoli and peppers (Palumbo et al., 2022). Hypobaric storage technique is highly suited for high value crops destined to export markets.

3.4 Smart Sensors and IoT Integration

Modern storage facilities are being increasingly equipped with Internet of Things (IoT) enabled smart sensors, ensuring continuous monitoring of critical environmental parameters, which include temperature, humidity, and gas concentrations (Alam et al., 2021). Real-time data analytics system helps in predictive maintenance and early detection of anomalies, in optimizing the storage conditions, thus reducing spoilage and waste (Zhong et al., 2023). The integration of IoT-enabled sensors to storage environments makes it possible to monitor critical parameters in real-time, including temperature, humidity, and gas composition (Lamberty et al., 2022). These sensors notify the stakeholders immediately where potential issues exist, hence timely intervention and minimization of losses.

Table 3. List of different vegetable and their benefits used under MA/CA storage method

Vegetable	Temperature	MA/CA		benefit
	(°C)	% O ₂	% CO ₂	
Artichokes	0-5	2-3	2-3	Good
Asparagus	0-5	15-20	5-10	Excellent
Beans	5-10	2-3	4-7	Fair
Beets	0-5	2-5	2-5	Fair
Broccoli	0-3	1-2	5-10	Excellent
Brussels sprouts	0-5	1-2	5-7	Good
Cabbage	0-5	2-3	5-7	Excellent
Cantaloupes	3-7	3-5	10-15	Good
Carrots	0-5	3-5	2-5	Fair
Cauliflower	0-2	2-3	2-5	Fair
Celery	0-5	1-1	0-5	Good
Corn, sweet	0-5	2-4	5-10	Good
Cucumbers	8-12	3-5	0-2	Fair
Honeydews	10-12	3-5	0-2	Fair
Leeks	0-5	1-2	3-5	Good
Lettuce	0-5	1-3	0-3	Good
Mushroom	0-3	Air	10-15	Fair
Okra	8-12	3-5	0-2	Fair
Onions, dry	0-5	1-2	0-5	Good
Onions, green	0-5	1-2	10-20	Fair
Peppers, bell	8-12	3-5	0-2	Fair
Peppers, chili	8-12	3-5	0-3	Fair
Potatoes	4-10	2-3	2-5	Fair
Radish	0-5	5-Jan	2-3	Fair
Spinach	0-5	18-21	10-20	Good
Tomato	15-20	5-Mar	0-3	Good

(Source, Kitinaja & Kader 2002)

Table 4. Maximum storage life (days) in normal atmosphere storage (NA), controlled atmosphere (CA) and low-pressure storage (LP)

Commodity	Maximum storage time (days)		
	Normal atmosphere storage	Controlled atmosphere	Low-pressure storage
Asparagus	14–21	Slight benefit – off-odors	28–42
Cucumber	9–14	14+ (slight benefit)	49
Green pepper	14–21	No benefit	50
Lime (Persian)	14–28	Juice loss, peel thickens	90
Mango (Haden)	14–21	No benefit	42
Mushroom	5	6	21
Papaya (Solo)	12	12+ (slight benefit)	28
Pear (Bartlett)	60	100	200
Protea (flower)	< 7	No benefit	30
Rose (flower)	7–14	No benefit	42
Spinach	10–14	Slight benefit	50
Strawberry	7	7+ (off-flavor)	21
Tomato (mature-green)	7–21	42	84

(Source, El-Ramady, 2015)

Table 5. Recommended temperature and relative humidity for fruits and vegetables and the approximate storage life under these conditions

Crop	Temperature (°C)	Relative humidity (%)	Storage life (days)
Artichoke	0	95–100	14–21
Asparagus	0–2	95–100	14–21
Bean (dry)	4–10	40–50	180–300
Beet (bunched)	0	98–100	10–14
Beet (topped)	0	98–100	120–180
Broad beans	0–2	90–98	7–14
Broccoli	0	95–100	14–21
Cabbage	0	98–100	150–180
Cactus leaves	2–4	90–95	14–21
Cantaloupe (half slip)	2–5	95	15
Cantaloupe (full slip)	0–2	95	5–14
Carrot (bunched)	0	95–100	14
Carrot (topped)	0	98–100	210–270
Cassava	0–5	85–96	30–60
Cauliflower	0	95–98	21–28
Celery	0	98–100	30–90
Chicory	0	95–100	14–21
Chinese cabbage	0	95–100	60–90
Chives	0	95–100	14–21
Cucumber	10–13	95	10–14
Eggplant	8–12	90–95	7
Garlic	0	65–70	180–210
Ginger	13	65	180
Green onions	0	95–100	21–28
Horse radish	–1 to 0	98–100	300–360
Jerusalem artichoke	–0.5 to 0	90–95	120–150
Kohlrabi	0	98–100	60–90

(Source, El-Ramady, 2015)

Table 6. Classification of some fruits and vegetables according to principal causes of postharvest losses and poor quality and in order of importance

Group	Examples	Principal causes of postharvest losses and poor quality (in order of importance)
Root vegetables	Carrots Beets Onions Garlic Potato Sweet Potato	Mechanical injuries Improper curing Sprouting and rooting Water loss (shriveling) Decay Chilling injury (subtropical and tropical root crops)
Leafy vegetables	Lettuce Chard Spinach Cabbage Green onions	Water loss (wilting) Loss of green color (yellowing) Mechanical injuries Relatively high respiration rates Decay
Flower vegetables	Artichokes Broccoli Cauliflower	Mechanical injuries Yellowing and other discolorations Abscission of florets Decay
Immature-fruit vegetables	Cucumbers Squash Eggplant Peppers Okra Snap beans	Over-maturity at harvest Water loss (shriveling) Bruising and other mechanical injuries Chilling injury Decay
Mature-fruit vegetables and fruits	Tomato Melons Citrus Bananas Mangoes Apples Grapes Stone fruits	Bruising Over-ripeness and excessive softening at harvest Water loss Chilling injury (chilling sensitive fruits) Compositional changes Decay

(Source, Kitinoja, and Kader, 2002)

3.5 Dynamic Controlled Atmosphere Systems

Dynamic controlled atmosphere (DCA) systems control the storage environment based on real-time data regarding the respiration rate and ethylene sensitivity of the vegetables being stored (Khan et al., 2024). This way, optimal preservation conditions are ensured with extended shelf life and quality preservation at minimal energy usage (Hu et al., 2019).

3.6 Modular Storage Modules

Customizable modular units with compartments suited to the individual needs of the various vegetables are provided (Laufenberg and Schulze (2009). This module is built to be capable of meeting diverse temperature and humidity requirements, thereby making it very

suitable for the storage of mixed produce in retail and supply chain operations (Codeluppi et al., 2019).

4. EMERGING TECHNOLOGIES

4.1 Nanotechnology

Nanotechnology has brought transformative solutions to the storage and preservation of vegetables (Sridhar et al., 2021). Applications in nano-coatings that serve as moisture barriers but also prevent microbial contamination are examples, as well as in nano-sorbents regulating ethylene levels to delay ripening and spoilage (Qadri et al., 2018). Recent advancements in nano-encapsulation also permit a more gradual release of antimicrobial agents, which can extend the shelf life of vegetables while ensuring safety and quality (Dubey et al., 2023).

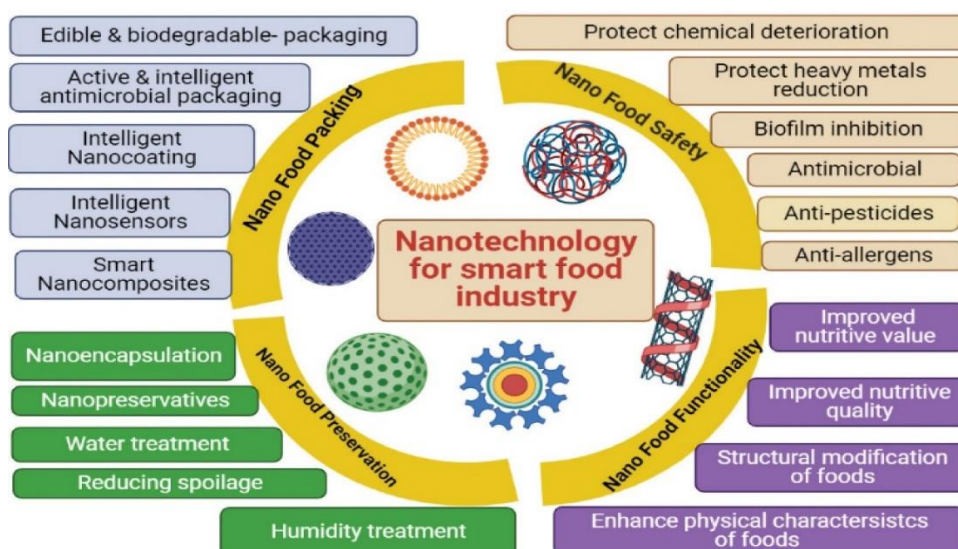


Fig. 2. Various applications of nanotechnology for improving food packing, preservation, safety and functionality
(Source, Lalpekhlu et al., 2024)

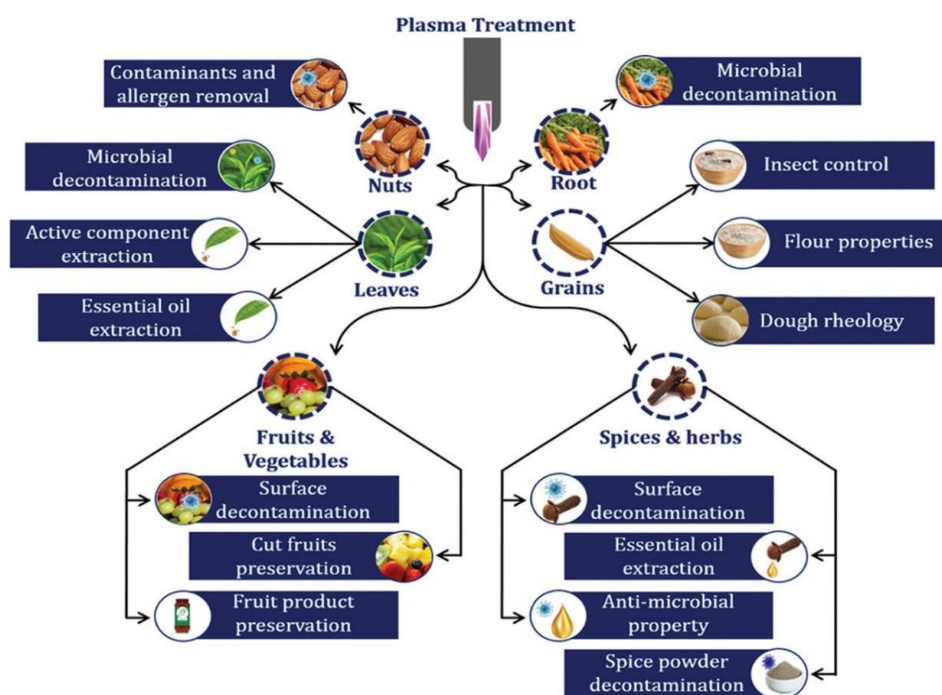


Fig. 3. Pictorial representation of different applications and advantages of plasma treatment of various food crops including nuts, fruits, vegetables, grains, root vegetables, spices and herbs in the food industry
(Source, Lalpekhlu et al., 2024)

4.2 Cryopreservation

Cryopreservation is ultra-low temperature storage, which is very useful for conserving high-value and genetically unique vegetable varieties

for the long-term availability of important germplasm and biodiversity (Panis et al., 2020). This is an important method especially for crops like onions, garlic, and other alliums, which are important for breeding programs

(Ochar and Kim 2023). The techniques of vitrification and encapsulation-dehydration have greatly improved the efficiency and applicability of cryopreservation for both commercial and research purposes (Benson et al., 2018).

4.3 Plasma Technology

Cold plasma treatments are coming up as a non-thermal solution to sterilize surfaces, inactivate pathogens, and preserve the freshness of vegetables (Asl et al., 2022). This technology generates reactive species that remove contaminants without affecting the nutritional and sensory quality of the produce (Thirumdas et al., 2015).

benefits, this technique presents technical challenges, trained operating personnel, and high installation costs, making it non-feasible for currently existing setups and systems (Lalpekhlua et al., 2024).

4.4 Artificial Intelligence (AI) Integration

AI-based tools are being used to predict the shelf life of vegetables, optimize storage conditions, and identify potential risks of spoilage (Pandey et al., 2023). Machine learning algorithms analyze environmental data and provide actionable insights to improve decision-making throughout the supply chain (Wang et al., 2024).

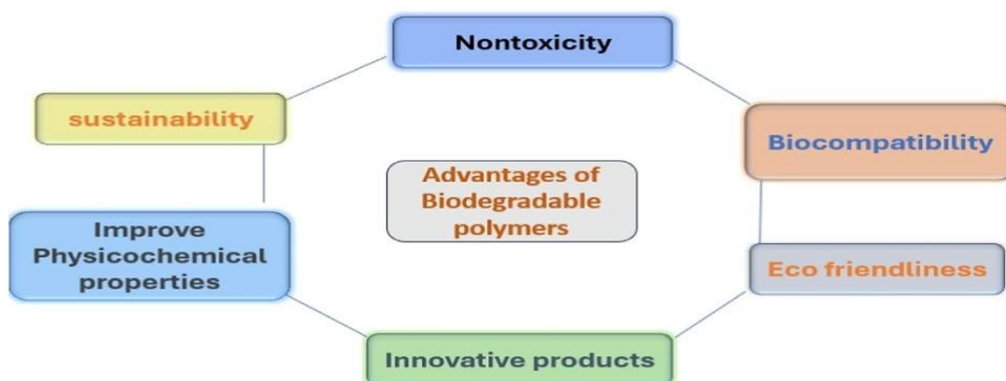


Fig. 4. Shows the advantages of biodegradable polymers
(Source, Ali, et al, 2024)

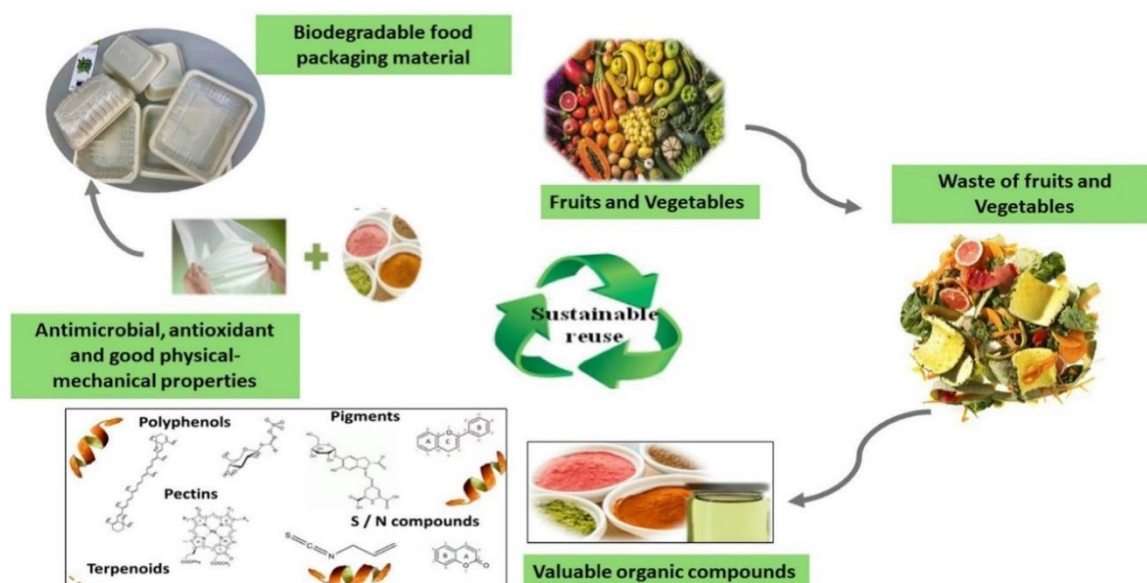


Fig. 5. Biopolymers Fruit and vegetable by-products Biodegradable packaging Edible films and coatings-
(Source, Ali et al., 2024)

4.5 Biopolymer-Based Smart Packaging

Biopolymers sensitized with sensors that monitor changing conditions in real time such as temperature, humidity, and gas composition emerge smart packaging solutions (Dăescu et al., 2024). Innovations that extend shelf lives also present the upside of increased consumer confidence through transparency and quality (Abady et al., 2024).

5. PACKAGING INNOVATIONS

Packaging innovation solutions for vegetables can offer extended shelf life, high quality, and prevention of post-harvest loss (Palumbo et al., 2022). This innovative focus has aligned the need with sustainability and efficiency to adapt into packaging technology specifically suited for all kinds of vegetables (Khan et al., 2021).

5.1 Biodegradable Packaging

There is a developing range of biodegradable materials that include PLA, starch-based films, and other plant-based polymers as environmentally friendly substitutes for traditional plastic packaging (Olawade et al., 2024). The said materials, while reducing the negative impact on the environment, can also protect goods from moisture and microbial contamination adequately.

To reduce plastic waste, biodegradable materials like polylactic acid (PLA) and starch-based films are now being researched to replace traditional plastics in packaging (Onyeaka et al., 2022). These materials break down naturally and do not

cause damage to the environment, thereby forming a circular economy (Rosenboom et al., 2022). Development of eco-friendly materials, such as polylactic acid (PLA) and starch-based films, to reduce plastic waste.

5.2 Active and Intelligent Packaging

5.2.1 Active packaging

In this, antimicrobial and antioxidant agents are impregnated in packaging materials, thus keeping vegetables fresh and safe (Kenyo, 2015). The antimicrobial agents kill microbes and also combat the action of free radicals which causes oxidative damage (Gavara, 2015).

Active packaging introduces antimicrobial agents, antioxidants, or moisture regulators into the material that will actively preserve the product (Yildirim et al., 2018). Such agents prevent the growth of microorganisms or oxidation and thus extend shelf life and reduce spoilage. Incorporation of antimicrobial and antioxidant agents into packaging materials (Singh et al., 2011).

5.2.2 Smart packaging

The smart packaging systems feature sensors and indicators that provide the customer with real-time information about the status of the vegetables (Alam et al., 2021). Features like freshness indicators, temperature trackers, and spoilage alerts improve the transparency of the supply chain and provide consumers with product quality information (Yousefi et al., 2019).



Fig. 6. Image of new active packaging
(Source, Dilucia, 2020)

It is the one that includes the integration of technology, like the indicators that would show the status of the product, such as spoilage or detect changes in environmental conditions like temperature and humidity (Kalpana et al., 2019). This helps in monitoring product quality throughout the supply chain. Indicators of spoilage or changes in environmental conditions.

5.3 Edible Coatings

Natural polymers such as chitosan, alginate, and carrageenan are used to develop edible coatings that form a protective layer around vegetables (Tavassoli-Kafrani et al., 2016). These coatings

minimize moisture loss, delay ripening, and reduce microbial spoilage (Salehi, 2020). Recent research has explored the addition of essential oils and bioactive compounds to enhance their functionality. Edible coatings based on natural polymers, such as chitosan and alginate, are applied to enhance shelf life (Kocira et al., 2021). The application of such a coating prevents the product from dehydration, oxidation, and microbial contamination, but it is safe for consumption and environment friendly (Tharanathan, 2003). Natural polymers such as chitosan and alginate have been utilized in creating edible coatings that prolong shelf life.

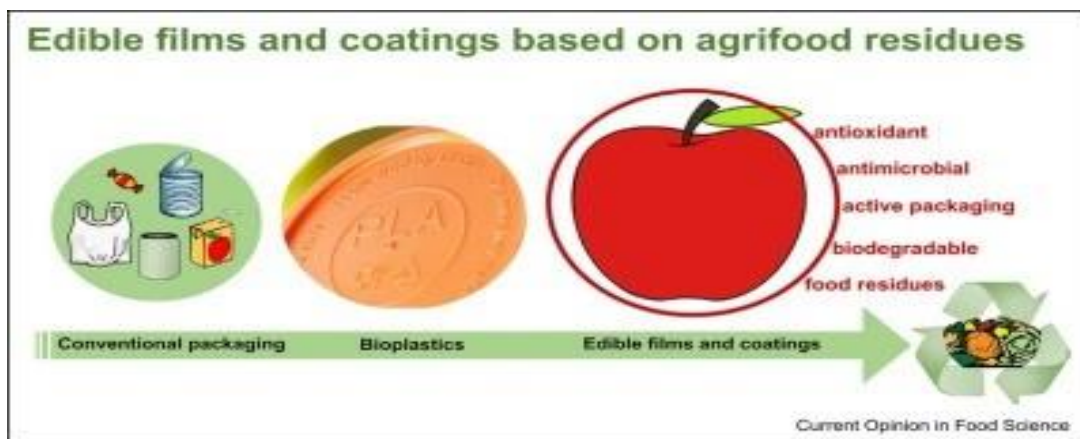


Fig. 7. Image of edible coating packaging
(Source, Gaspar, and Braga, 2023)

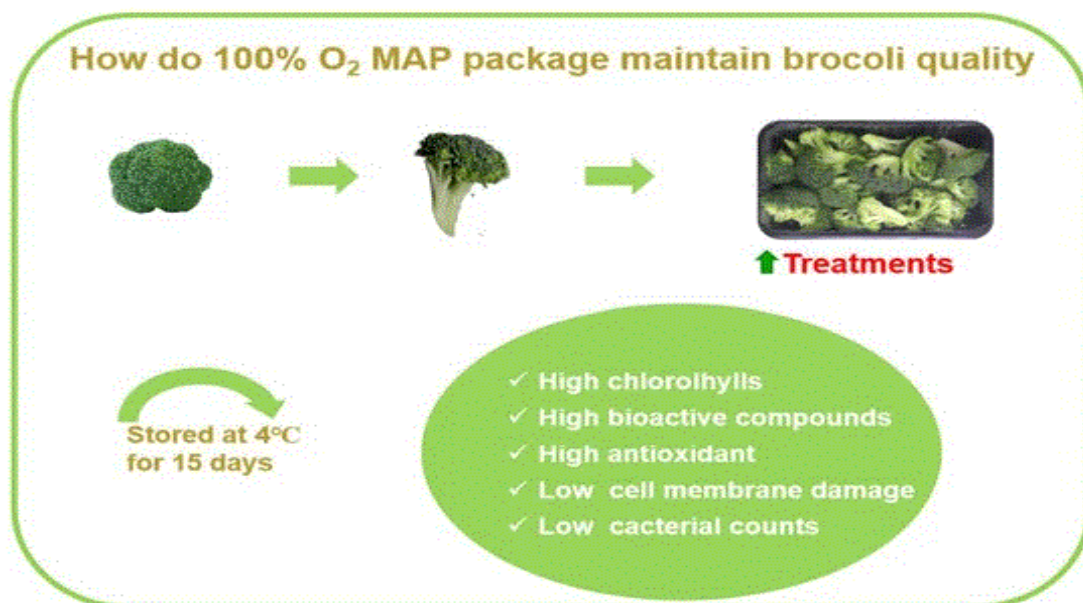


Fig. 8. Image of broccoli stored by MAP
(Source, Dai, et al., 2023)

5.4 Modified Atmosphere Packaging (MAP)

Modified Atmosphere Packaging (MAP) is a novel post-harvest technology used to extend the shelf life of fresh vegetables by modifying the gaseous environment in the packaging (Mangaraj & Goswami 2009). The technique reduces the respiration rate and microbial activity, thereby slowing down spoilage and preserving the nutritional and sensory attributes of the produce. MAP involves changing the gaseous composition inside the packaging to slow down respiration and microbial growth (Ben-Yehoshua et al., 2005). Modern MAP systems change gas levels according to environmental parameters so that they would remain at optimally favorable conditions for different types of vegetables.

5.4.1 Dynamic gas adjustment

Today advanced MAP systems come with dynamic features whereby oxygen (O₂), carbon dioxide (CO₂), and nitrogen (N₂) levels should be regulated according to environmental changes and the respiration rate of packaged vegetables (Sebranek and Houser 2017). In this way, the vegetables should be maintained at consistently optimal conditions for a variety of vegetable types (Ben-Yehoshua et al., 2005).

5.4.2 High-barrier materials

Modern MAP utilizes high-barrier films that effectively regulate gas exchange, humidity, and condensation. These materials, often integrated with nanotechnology, provide superior control over internal packaging conditions, further enhancing vegetable preservation.

5.4.3 Ethylene regulation

Ethylene, a ripening hormone, is actively managed in MAP through the use of ethylene scavengers embedded in the packaging material. This significantly slows down the ripening process and prevents premature deterioration.

5.4.4 Integration of active packaging

MAP is significantly integrated with antimicrobial and antioxidant agents in active packaging to provide better benefits of atmospheric control and protection of the product against microbial spoilage.

5.4.5 Sustainability improvements

The improvements have also centered on green and sustainable MAP with biodegradable films and the use of renewable resources for consistency with sustainability ideals but not reducing functionality.

Utilizing all these discoveries, MAP persists and is transformed as the foundational unit for storing perishable vegetables long beyond harvest and decreases the rates of wasting products plus improved market value.

6. NANOTECHNOLOGY IN PACKAGING

Nanocomposites are reinventing packaging technologies where it affords superior barriers towards oxygen and water vapours; and against microbes and even others, helping package longer against various factors like damages (Mihindukulasuriya et al., 2014). In addition, the nano-sensors integrated with the packaging material help in time-based monitoring, which includes real-time temperature, humidity, and freshness conditions (Sagar et al., 2014). Hence, the storage period will be appropriate and less wasted.

Nanocomposite material has improved the barrier properties by including them within the packaging design, thus oxygen and moisture are efficiently prevented (Primožič et al., 2021). Furthermore, nano-sensors integrated in packaging enable measuring the freshness along with the appropriate storage conditions precisely (Babu, 2022).

7. SUSTAINABLE PACKAGING DESIGNS

Packaging solutions are now becoming lighter and reusable in a bid to minimize environmental impact (Marsh & Bugusu 2007). Sustainable designs include collapsible crates and stackable containers that will enhance logistical efficiency while maintaining the integrity of produce during transport (Yao et al., 2024). Such innovations reduce carbon footprints and waste associated with packaging (Castillo-Benancio et al., 2022). Innovations in light and reusable packaging designs are meant to minimize waste and reduce carbon footprints. Innovations such as collapsible crates and stackable containers enhance the efficiency of logistics while preserving produce integrity during transportation (Ait et al., 2019).

8. POST-HARVEST LOSS REDUCTION STRATEGIES

Reducing post-harvest losses involves a multi-layered challenge combining technical, infrastructural, and policy-driven interventions (Nkolanyane, 2021). Strategies are designed to address the prime factors that create wastage in vegetable supply chains and ensure that these chains become economically viable and sustainable (Verghese et al., 2015).

8.1 Training and Capacity Building

The development of best management of harvesting, grading, sorting and packaging practices shall reduce losses associated with the processing of perishables (Kitinoja & Kader 2002). Workshops, extension programs, and use of digital forums will be at the forefront.

Community-Led Initiatives are aimed at establishing post-harvest management collective responsibility through projects such as local cold storage as well as collaborative resource utilization approaches.

8.2 Infrastructure Investment

8.2.1 Cold chain expansion

Adequate cold chains with precooling facilities and refrigerated modes of transport have been developed together with cold rooms to ensure complete temperature control down the supply line (Zhao et al., 2018).

8.2.2 Packhouses and processing units

Creating packhouses, provided with grading, sorting, and cleaning facilities improves vegetable quality but generates employment for people in the countryside (Walsh, 2018). Further processing like dehydration and freezing provides greater utility for the surplus product.

8.3 Policy and Incentives

8.3.1 Subsidy to adopt technologies

Subsidy to take high technology of post-harvesting process including smart storage facility and precision harvesting tools attracts the farmers for taking the high technological practice in cultivation (Sudheer et al., 2021).

8.3.2 Supportive regulatory frameworks

Policies that enable access to low-cost credit, insurance, and public-private partnerships spur investment in post-harvest infrastructure and research (Chege et al., 2024).

8.4 Technological Integration

Digital Monitoring Systems: IoT-based solutions integrate into real-time monitoring of storage and transportation conditions, reducing losses through timely interventions (Grover et al., 2024). Predictive analytics powered by AI can predict risks of spoilage and optimize logistics.

Mobile Applications: Mobile applications user-friendly can provide information regarding market prices, weather forecast, and best practices to the farmer for proper decision-making (Burman et al., 2024).

8.5 Market Connectivity and Awareness

Strengthening Supply Chains: Connecting the farmer directly to markets, which could be an e-commerce platform as well, reduce the involvement of intermediaries, and therefore there is a good price realization (Li & Zhang 2024).

Consumer Education: Raising consumer education about handling and storage of vegetables at their home can result in a great amount of reduction of wastage from households (Hebrok & Boks 2017).

By combining these approaches, stakeholders along the value chain can collectively reduce post-harvest losses, improve vegetable quality, and contribute to global food security and sustainability objectives (Magalhães et al., 2022).

9. CHALLENGES AND FUTURE DIRECTIONS

9.1 Challenges

9.1.1 High initial investment costs

Advanced storage and handling systems are often capital-intensive, which deters adoption among smallholder farmers and other stakeholders in resource-constrained environments.

Limited awareness and technical knowledge about current post-harvest technologies and best practices. In the context of rural regions, it makes implementation less effective.

9.1.2 Inadequate infrastructure

There is a major constraint of poor connectivity by roads, cold chain networks, and supply of electricity in several developing regions.

9.1.3 High perishability

Vegetables inherently have a very short shelf life that requires prompt and efficient post-harvest intervention, which lacks in many instances.

9.1.4 Market volatility

The variability of market prices and limited accessibility to fair trade networks raise the financial risk to farmers and traders.

9.2 Future Directions

9.2.1 Research and development

The future innovations in packaging and storage will emphasize the creation of low-cost scalable technologies that are applicable to small-scale farmers and producers. The emphasis of the research will be the development of cost-effective high-performance materials, made accessible to more agricultural stakeholders, such as innovative biodegradable packaging, active and intelligent packaging technologies, and materials for extending shelf life while maintaining food safety.

9.2.2 Digital integration

The integration of digital technologies will be pivotal in transforming supply chains. Blockchain technology can ensure transparency, traceability, and authenticity of products from farm to table, providing consumers and businesses with real-time information on product quality and origin. AI-driven platforms will enable smarter decision-making by optimizing logistics, inventory management, and predicting product demand. These technologies will lead to a more efficient, resilient, and sustainable supply chain for agricultural products. The use of digital tools such as blockchain for traceability, AI for predictive analytics, and IoT for real-time monitoring can revolutionize the efficiency and transparency of supply chains.

9.2.3 Public-private partnerships

Governments, private sector entities, and research institutions can collaborate to enhance funding, infrastructure, and knowledge dissemination.

9.2.4 Sustainability

Sustainability will remain the heart of packaging and storage systems, with an emphasis on promoting circular economy principles. Packaging materials will be designed for reuse, recycling, or biodegradability, reducing waste and conserving resources. Innovations in storage systems will be focused on reducing energy consumption, using renewable materials, and optimizing storage conditions to minimize spoilage and waste. These will be part of broader environmental goals and assist industries in the transition to more sustainable practices aligned with global sustainability frameworks. Adopting circular economy principles, such as recycling packaging materials and repurposing agricultural waste, can reduce environmental impact and promote resource efficiency.

9.2.5 Low-cost innovations

R&D should focus on affordable, scalable technologies for small-scale and resource-constrained farmers. Examples include solar-powered cold storage units and low-cost moisture barriers.

9.2.6 Capacity building programs

Expanding training programs to educate farmers and supply chain workers on modern post-harvest techniques and technologies will ensure wider adoption and greater effectiveness.

9.2.7 Policy reforms

Governments should implement policies to incentivize technology adoption, provide financial support, and strengthen market linkages for smallholder farmers.

9.2.8 Global cooperation

International cooperation and knowledge exchange may accelerate innovation towards addressing common post-harvest problems in vegetable management.

Through progress in these areas, the future of packaging and storage will not only enhance the

preservation and transportation of products but also contribute to lowering the environment footprint and supporting small-scale farmer livelihoods.

10. CONCLUSION

Advances in post-harvest handling and storage of vegetables have greatly reduced losses, improved quality, and ensured food security. The integration of cutting-edge technologies with traditional practices holds much promise for the sustainable supply chain of vegetables. However, addressing the economic and infrastructural barriers will be crucial in fully realizing the benefits of such innovations, especially in developing countries. Future research and collaborative efforts are essential to enhance the accessibility and affordability of these innovations across the globe.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

- Abady, M. M., Shawky, A. M., Sakr, F. A., Mohammed, D. M., & Goda, E. S. (2024). Recent Advancements in Biosensors Using Biopolymers. In *Bio-Based Polymers: Farm to Industry. Volume 2: Current Trends and Applications* (pp. 81-112). American Chemical Society.
- Ait-Oubahou, A., Hanani, Z. N., & Jamilah, B. (2019). Packaging. In *Postharvest technology of perishable horticultural commodities* (pp. 375-399). Woodhead Publishing.
- Alam, A. U., Rathi, P., Beshai, H., Sarabha, G. K., & Deen, M. J. (2021). Fruit quality monitoring with smart packaging. *Sensors*, 21(4), 1509.
- Ali, M. Q., Ahmad, N., Azhar, M. A., Munaim, M. S. A., Hussain, A., & Mahdi, A. A. (2024). An overview: exploring the potential of fruit and vegetable waste and by-products in food biodegradable packaging. *Discover Food*, 4(1), 130.
- Amjad, W., Munir, A., Akram, F., Parmar, A., Precoppe, M., Asghar, F., & Mahmood, F. (2023). Decentralized solar-powered cooling systems for fresh fruit and vegetables to reduce post-harvest losses in developing regions: a review. *Clean Energy*, 7(3), 635-653.
- Anjali, Jena, A., Bamola, A., Mishra, S., Jain, I., Pathak, N., ... & Akhtar, S. (2024). State-of-the-art non-destructive approaches for maturity index determination in fruits and vegetables: Principles, applications, and future directions. *Food Production, Processing and Nutrition*, 6(1), 56.
- Ars, P. M., & Selvakumar, R. (2013). *Glaustas horticulture*. New vishal publications.
- Asl, P. J., Rajulapati, V., Gavahian, M., Kapusta, I., Putnik, P., Khaneghah, A. M., & Marszałek, K. (2022). Non-thermal plasma technique for preservation of fresh foods: A review. *Food Control*, 134, 108560.
- Babu, P. J. (2022). Nanotechnology mediated intelligent and improved food packaging. *International Nano Letters*, 12(1), 1-14.
- Benson, E. E., Harding, K., Ryan, M., Petrenko, A., Petrenko, Y., & Fuller, B. (2018). Alginate encapsulation to enhance biopreservation scope and success: a multidisciplinary review of current ideas and applications in cryopreservation and non-freezing storage. *Cryoletters*, 39(1), 14-38.
- Ben-Yehoshua, S., Beaudry, R. M., Fishman, S., Jayanty, S., & Mir, N. (2005). Modified atmosphere packaging and controlled atmosphere storage. *Environmentally friendly technologies for agricultural produce quality*, 61-112.
- Bisht, A., & Singh, S. P. (2024). Postharvest Losses and Management of Horticultural Produce: A Review. *Journal of Scientific Research and Reports*, 30, 305-320.
- Burg SP (2004) Postharvest physiology and hypobaric storage of fresh produce. CABI Publishing/ CAB International, Wallingford
- Burman, R. R., Mahra, G. S., & Mallick, S. (2024). Mobile applications for real time market information and decision support in horticultural crops. *Indian Horticulture*, 69(6), 77-80.
- Castillo-Benancio, S., Alvarez-Risco, A., Esquerre-Botton, S., Leclercq-Machado, L., Calle-Nole, M., Morales-Ríos, F., ... &

- Del-Aguila-Arcenales, S. (2022). Circular economy for packaging and carbon footprint. In *Circular economy: Impact on carbon and water footprint* (pp. 115-138). Singapore: Springer Singapore.
- Chege, C., Onyango, K., Bodjerenou, S., Schmidt, M., Heike, H., & Ostermann, H. (2024). Adapting green innovation centers to climate change: Reducing post-harvest loss and improving processing for target groups.
- Codeluppi, G., Cilfone, A., Davoli, L., & Ferrari, G. (2019, October). VegIoT garden: a modular IoT management platform for urban vegetable gardens. In *2019 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)* (pp. 121-126). IEEE.
- Dăescu, D. I., Dreavă, D. M., Todea, A., Peter, F., & Păușescu, I. (2024). Intelligent Biopolymer-Based Films: Promising New Solutions for Food Packaging Applications. *Polymers*, 16(16), 2256.
- Dai, Y., Zhao, X., Zuo, J., & Zheng, Y. (2023). Effect of 100% oxygen-modified atmosphere packaging on maintaining the quality of fresh-cut broccoli during refrigerated storage. *Foods*, 12(7), 1524.
- Deep, N., Mehta, D. K., & Sharma, N. (2024). ADVANCED POST-HARVEST TECHNOLOGIES. *FUNDAMENTALS AND INNOVATIONS*, 194.
- Dilucia, F., Lacivita, V., Conte, A., & Del Nobile, M. A. (2020). Sustainable use of fruit and vegetable by-products to enhance food packaging performance. *Foods*, 9(7), 857.
- Dubey, N., Chitranshi, S., Dwivedi, S. K., & Sharma, A. (2023). Postharvest physiology, value chain advancement, and nanotechnology in fresh-cut fruits and vegetables. In *Nanotechnology Horizons in Food Process Engineering* (pp. 99-132). Apple Academic Press.
- Elik, A., Yanik, D. K., Istanbulu, Y., Guzelsoy, N. A., Yavuz, A., & Gogus, F. (2019). Strategies to reduce post-harvest losses for fruits and vegetables. *Strategies*, 5(3), 29-39.
- El-Ramady, H. R., Domokos-Szabolcsy, É., Abdalla, N. A., Taha, H. S., & Fâri, M. (2015). Postharvest management of fruits and vegetables storage. *Sustainable Agriculture Reviews: Volume 15*, 65-152.
- Garcia, E. D. S., Quaresma, N., Aemro, Y. B., Coimbra, A. P., & De Almeida, A. T. (2024). Cooling with the sun: Empowering off-grid communities in developing countries with solar-powered cold storage systems. *Energy Research & Social Science*, 117, 103686.
- Gaspar, M. C., & Braga, M. E. (2023). Edible films and coatings based on agrifood residues: a new trend in the food packaging research. *Current opinion in food science*, 50, 101006.
- Gavara, R. (2015). *Practical Guide to Antimicrobial Active Packaging*. Smithers Pira.
- Gayathiri, E., Prakash, P., Karmegam, N., Varjani, S., Awasthi, M. K., & Ravindran, B. (2022). Biosurfactants: potential and eco-friendly material for sustainable agriculture and environmental safety—a review. *Agronomy*, 12(3), 662.
- Goh, J. Y., Md Yunus, Y., & Mohamed Ali, M. S. (2025). Fresh Fruit Bunch Ripeness Classification Methods: A Review. *Food and Bioprocess Technology*, 18(1), 183-206.
- Gouda, M. H. B., & Duarte-Sierra, A. (2024). An Overview of Low-Cost Approaches for the Postharvest Storage of Fruits and Vegetables for Smallholders, Retailers, and Consumers. *Horticulturae*, 10(8), 803.
- Grover, V., Balusamy, B. B., Milanova, M. G., & Felix, A. Y. (2024). *Blockchain, IoT, and AI Technologies for Supply Chain Management: Apply Emerging Technologies to Address and Improve Supply Chain Management*. Springer Nature.
- Han, J. W., Zuo, M., Zhu, W. Y., Zuo, J. H., Lü, E. L., & Yang, X. T. (2021). A comprehensive review of cold chain logistics for fresh agricultural products: Current status, challenges, and future trends. *Trends in Food Science & Technology*, 109, 536-551.
- Hayat, U., Li, W., Bie, H., Liu, S., Guo, D., & Cao, K. (2023). An Overview on Post-Harvest Technological Advances and Ripening Techniques for Increasing Peach Fruit Quality and Shelf Life. *Horticulturae*, 10(1), 4.
- Hebrok, M., & Boks, C. (2017). Household food waste: Drivers and potential intervention points for design—An extensive review. *Journal of Cleaner Production*, 151, 380-392.
- Hu, B., Sun, D. W., Pu, H., & Wei, Q. (2019). Recent advances in detecting and regulating ethylene concentrations for shelf-life extension and maturity control of

- fruit: A review. *Trends in Food Science & Technology*, 91, 66-82.
- Jahangiri, F., Mohanty, A. K., & Misra, M. (2024). Sustainable biodegradable coatings for food packaging: challenges and opportunities. *Green Chemistry*.
- Jurić, M., Bandić, L. M., Carullo, D., & Jurić, S. (2024). Technological advancements in edible coatings: Emerging trends and applications in sustainable food preservation. *Food bioscience*, 103835.
- Kalpana, S., Priyadarshini, S. R., Leena, M. M., Moses, J. A., & Anandharamakrishnan, C. (2019). Intelligent packaging: Trends and applications in food systems. *Trends in Food Science & Technology*, 93, 145-157.
- Kenýó, C. (2015). *Active packaging materials: factors, mechanism, efficiency* (Doctoral dissertation, Budapest University of Technology and Economics (Hungary)).
- Khan, M. R., Muhammad, A., Guo, Y., Hashmi, M. S., & Ahmad, R. Dynamic Controlled Atmosphere Technology for Fruits and Vegetables. In *Sustainable Postharvest Technologies for Fruits and Vegetables* (pp. 86-94). CRC Press. 1st Edition First Published 2024
- Khan, N., Ray, R. L., Kassem, H. S., Hussain, S., Zhang, S., Khayyam, M., ... & Asongu, S. A. (2021). Potential role of technology innovation in transformation of sustainable food systems: A review. *Agriculture*, 11(10), 984.
- Kiaya, V. (2014). Post-harvest losses and strategies to reduce them. *Technical Paper on Postharvest Losses, Action Contre la Faim (ACF)*, 25(3), 1-25.
- Kitinoja, L., & Kader, A. A. (2002). *Small-scale postharvest handling practices: a manual for horticultural crops*. California: University of California, Davis, Postharvest Technology Research and Information Center.
- Kitinoja, L., & Kader, A. A. (2002). *Small-scale postharvest handling practices: a manual for horticultural crops*. California: University of California, Davis, Postharvest Technology Research and Information Center.
- Kocira, A., Kozłowicz, K., Panasiewicz, K., Staniak, M., Szpunar-Krok, E., & Horthyńska, P. (2021). Polysaccharides as edible films and coatings: Characteristics and influence on fruit and vegetable quality—A review. *Agronomy*, 11(5), 813.
- Kumar, A., & Harsha, S. P. (2024). A systematic literature review of defect detection in railways using machine vision-based inspection methods. *International Journal of Transportation Science and Technology*.
- Lalpekhlua, K., Tirkey, A., Saranya, S., & Babu, P. J. (2024). Post-harvest Management Strategies for Quality Preservation in Crops. *International Journal of Vegetable Science*, 30(5), 587-635.
- Lamberty, A., & Kreyenschmidt, J. (2022). Ambient parameter monitoring in fresh fruit and vegetable supply chains using internet of things-enabled sensor and communication technology. *Foods*, 11(12), 1777.
- Laufenberg, G., & Schulze, N. (2009). A modular strategy for processing of fruit and vegetable wastes into value-added products. In *Handbook of waste management and co-product recovery in food processing* (pp. 286-353). Woodhead Publishing.
- Li, G., & Zhang, H. (2024). The Efficiency and Challenges of E-Commerce Logistics in Enhancing Market Access for Agricultural Products in Rural China. *Law and Economy*, 3(2), 31-43.
- Luerssen, C., Sekhar, C., Cheong, D., & Reindl, T. (2020). Solar-Powered Cooling for the Remote Tropics. *Sustainable Energy Solutions for Remote Areas in the Tropics*, 31-62.
- Magalhães, V. S., Ferreira, L. M. D., & Silva, C. (2022). Prioritising food loss and waste mitigation strategies in the fruit and vegetable supply chain: A multi-criteria approach. *Sustainable Production and Consumption*, 31, 569-581.
- Makule, E., Dimoso, N., & Tassou, S. A. (2022). Precooling and cold storage methods for fruits and vegetables in Sub-Saharan Africa—A review. *Horticulturae*, 8(9), 776.
- Mangaraj, S., & Goswami, T. K. (2009). Modified atmosphere packaging of fruits and vegetables for extending shelf-life-A review. *Fresh produce*, 3(1), 1-31.
- Marsh, K., & Bugusu, B. (2007). Food packaging—roles, materials, and environmental issues. *Journal of food science*, 72(3), R39-R55.
- Metcalfe, R. (2019). *Food routes: growing bananas in Iceland and other tales from the logistics of eating*. MIT Press.
- Mihindukulasuriya, S. D. F., & Lim, L. T. (2014). Nanotechnology development in food packaging: A review. *Trends in Food Science & Technology*, 40(2), 149-167.

- Nama, P. R. A. T. H. Y. U. S. H. A. (2022). Cost management and optimization in automation infrastructure. *Iconic Research and Engineering Journals*, 5(12), 276-285.
- Nkolanyane, T. M. (2021). *Enhancing food security through disaster risk reduction and climate change adaptation policies and legislation: South African context* (Doctoral dissertation, North-West University (South Africa)).
- Ochar, K., & Kim, S. H. (2023). Conservation and Global Distribution of Onion (*Allium cepa* L.) Germplasm for Agricultural Sustainability. *Plants*, 12(18), 3294.
- Olawade, D. B., Wada, O. Z., & Ige, A. O. (2024). Advances and recent trends in plant-based materials and edible films: a mini-review. *Frontiers in Chemistry*, 12, 1441650.
- Onyeaka, H., Obileke, K., Makaka, G., & Nwokolo, N. (2022). Current research and applications of starch-based biodegradable films for food packaging. *Polymers*, 14(6), 1126.
- Palumbo, M., Attolico, G., Capozzi, V., Cozzolino, R., Corvino, A., de Chiara, M. L. V., ... & Cefola, M. (2022). Emerging postharvest technologies to enhance the shelf-life of fruit and vegetables: an overview. *Foods*, 11(23), 3925.
- Pandey, V. K., Srivastava, S., Dash, K. K., Singh, R., Mukarram, S. A., Kovács, B., & Harsányi, E. (2023). Machine Learning algorithms and fundamentals as Emerging Safety Tools in Preservation of fruits and vegetables: a review. *Processes*, 11(6), 1720.
- Panis, B., Nagel, M., & van Den Houwe, I. (2020). Challenges and prospects for the conservation of crop genetic resources in field genebanks, in in vitro collections and/or in liquid nitrogen. *Plants*, 9(12), 1634.
- Primožič, M., Knez, Ž., & Leitgeb, M. (2021). (Bio) Nanotechnology in food science—food packaging. *Nanomaterials*, 11(2), 292.
- Qadri, O. S., Younis, K., Srivastava, G., & Srivastava, A. K. (2018). Nanotechnology in packaging of fresh fruits and vegetables. In *Emerging postharvest treatment of fruits and vegetables* (pp. 147-166). Apple Academic Press.
- Rajapaksha, L., Gunathilake, D. M. C. C., Pathirana, S. M., & Fernando, T. (2021). Reducing post-harvest losses in fruits and vegetables for ensuring food security—Case of Sri Lanka. *MOJ Food Process Technols*, 9(1), 7-16.
- Rao, C. G. (2015). *Engineering for storage of fruits and vegetables: cold storage, controlled atmosphere storage, modified atmosphere storage*. Academic Press.
- Rosenboom, J. G., Langer, R., & Traverso, G. (2022). Bioplastics for a circular economy. *Nature Reviews Materials*, 7(2), 117-137.
- Rutta, E. W. (2022). *Barriers Impeding the Deployment and Uptake of Solar-Powered Cold Storage Technologies for Postharvest Loss Reduction in Tomato Value Chain in Africa: Empirical Evidence from Tanzania* (Doctoral dissertation, Queen's University (Canada)).
- Saengwong-ngam, R., Saengrayap, R., Rattanakaran, J., Arwatchananukul, S., Aunsri, N., Tontiwattanukul, K., ... & Chaiwong, S. (2024). Cushion performance of eco-friendly natural rubber latex foam composite with bamboo leaf fiber for impact protection of guava. *Postharvest Biology and Technology*, 208, 112663.
- Sagar, N. A., Kumar, N., Choudhary, R., Bajpai, V. K., Cao, H., Shukla, S., & Pareek, S. (2022). Prospecting the role of nanotechnology in extending the shelf-life of fresh produce and in developing advanced packaging. *Food Packaging and Shelf Life*, 34, 100955.
- Salehi, F. (2020). Edible coating of fruits and vegetables using natural gums: A review. *International Journal of Fruit Science*, 20(sup2), S570-S589.
- Sebranek, J. G., & Houser, T. A. (2017). Modified atmosphere packaging. In *Advanced technologies for meat processing* (pp. 615-646). CRC Press.
- Septembre-Malaterre, A., Remize, F., & Pouchet, P. (2018). Fruits and vegetables, as a source of nutritional compounds and phytochemicals: Changes in bioactive compounds during lactic fermentation. *Food research international*, 104, 86-99.
- Singh, P., Wani, A. A., & Saengerlaub, S. (2011). Active packaging of food products: recent trends. *Nutrition & Food Science*, 41(4), 249-260.
- Sridhar, A., Ponnuchamy, M., Kumar, P. S., & Kapoor, A. (2021). Food preservation techniques and nanotechnology for increased shelf life of fruits, vegetables, beverages and spices: a review.

- Environmental Chemistry Letters*, 19, 1715-1735.
- Sudheer, K. P., Sreelakshmi, K. U., & Prabha, V. (2021). Post-harvest Management Through Convergence of Innovation and Technology. In *Innovations in Agriculture for a Self-Reliant India* (pp. 595-625). CRC Press.
- Tavassoli-Kafrani, E., Shekarchizadeh, H., & Masoudpour-Behabadi, M. (2016). Development of edible films and coatings from alginates and carrageenans. *Carbohydrate polymers*, 137, 360-374.
- Tharanathan, R. N. (2003). Biodegradable films and composite coatings: past, present and future. *Trends in food science & technology*, 14(3), 71-78.
- Thirumdas, R., Sarangapani, C., & Annapure, U. S. (2015). Cold plasma: a novel non-thermal technology for food processing. *Food biophysics*, 10, 1-11.
- Tyagi, S. K., & Khire, A. R. (2018). *Vegetable crops at a glance*. Scientific Publishers-Competition Tutor.
- van Gogh, B., Boerrigter, H., Noordam, M., Ruben, R., & Timmermans, T. (2017). *Post-harvest loss reduction: a value chain perspective on the role of post-harvest management in attaining economically and environmentally sustainable food chains* (No. 1751). Wageningen Food & Biobased Research.
- Verghese, K., Lewis, H., Lockrey, S., & Williams, H. (2015). Packaging's role in minimizing food loss and waste across the supply chain. *Packaging Technology and Science*, 28(7), 603-620.
- Verma, L. R., & Joshi, V. K. (2000). Post-harvest technology of fruits and vegetables. *Post harvest technology of fruits and vegetables*, 1(1), 1-76.
- Walsh, K. B. (2018). Fruit and vegetable packhouse: Technologies for assessing fruit quantity and quality. In *Advances in Agricultural Machinery and Technologies* (pp. 367-395). CRC Press.
- Wang, D., Zhang, M., Li, M., & Lin, J. (2024). Fruits and vegetables preservation based on AI technology: research progress and application prospects. *Computers and Electronics in Agriculture*, 226, 109382.
- Yahia, E. M. (Ed.). (2019). *Postharvest technology of perishable horticultural commodities*. Woodhead Publishing.
- Yao, K. C., Hsieh, H. H., Li, K. Y., Xu, J. R., Ho, W. S., Huang, W. L., ... & Tseng, Y. J. (2024). Sustainable Packaging Solutions: Food Engineering and Biodegradable Materials. *Designs*, 8(6), 133.
- Yildirim, S., Röcker, B., Pettersen, M. K., Nilsen-Nygaard, J., Ayhan, Z., Rutkaite, R., ... & Coma, V. (2018). Active packaging applications for food. *Comprehensive Reviews in food science and food safety*, 17(1), 165-199.
- Yousefi, H., Su, H. M., Imani, S. M., Alkhalidi, K., M. Filipe, C. D., & Didar, T. F. (2019). Intelligent food packaging: A review of smart sensing technologies for monitoring food quality. *ACS sensors*, 4(4), 808-821.
- Zhao, H., Liu, S., Tian, C., Yan, G., & Wang, D. (2018). An overview of current status of cold chain in China. *International journal of refrigeration*, 88, 483-495.
- Zhong, X., Zhang, M., Tang, T., Adhikari, B., & Ma, Y. (2023). Advances in intelligent detection, monitoring, and control for preserving the quality of fresh fruits and vegetables in the supply chain. *Food Bioscience*, 103350.

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