Advancements in Post-Harvest Handling and Storage of Vegetables: A Review

Abstract

In a broad sense, vegetables are perishable products and undergo substantial qualitative and quantitative losses after harvest. Advances in handling and storage technologies during the post-harvest phase have thus emerged as critical interventions for maintaining quality, extending shelf life, and minimizing waste. This review discusses contemporary developments in postharvest management, including new methods of harvesting, innovative and new methods of storage, and advanced packaging technologies. It also covers some of the problems and future scopes of sustainable and efficient vegetable post-harvest systems. Among all perishable commodities, vegetables are one that suffers the maximum qualitative and quantitative losses after the harvest. Present developments in handling and storage post-harvest technologies have played a vital role in solving this problem. 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, cutting-edge storage systems, and smart packaging technologies. The article further highlights some of the gaps already observed such as infrastructural deficiencies, which offer great future scope to create efficient, sustainable vegetable post-harvest systems.

Keywords: Smart Packaging, storage, vegetable and post-harvest loss

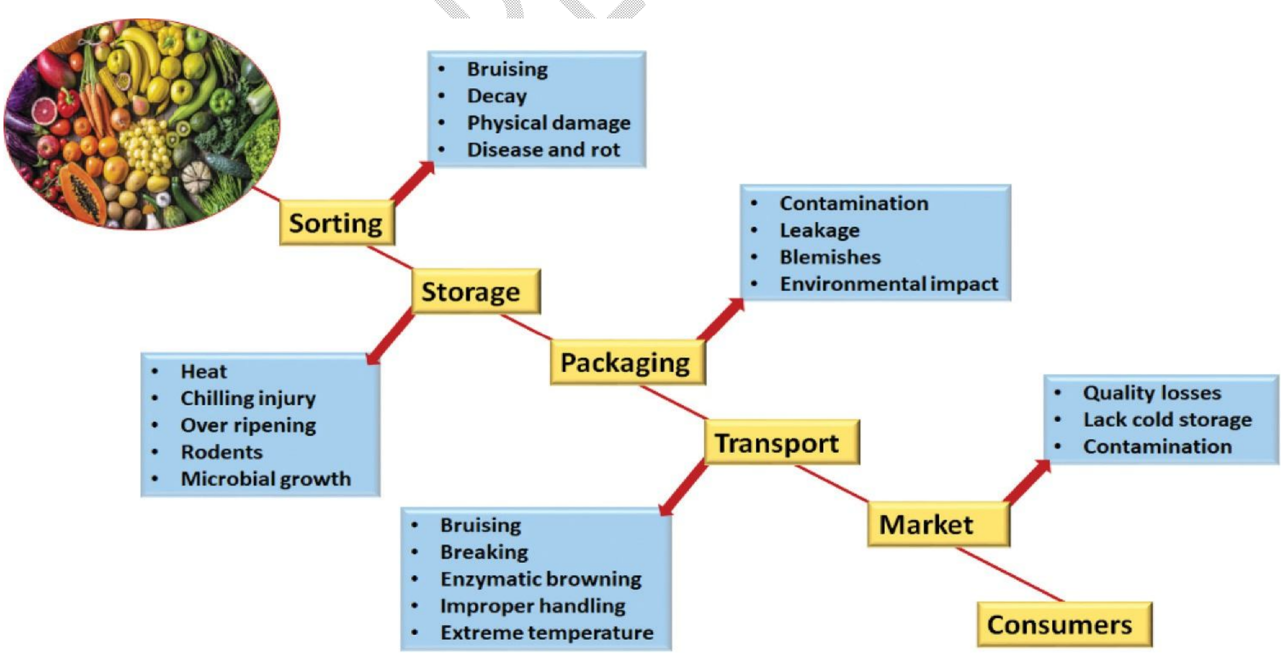
1. Introduction

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 and vulnerable to rapid deterioration during post-harvest, they are quite significant. It is often said that the percentage of post-harvest loss in vegetables may be more than 30%, especially in developing countries with scarce infrastructure, inefficient cold chains, and poor storage (Kiaya, V. 2014). 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, A., and Singh, S. P. 2024). These technologies also have the potential to enhance sustainability by reducing waste and improving the efficiency of vegetable supply chains. Vegetables are very important constituents of a healthy diet, providing crucial nutrients 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, 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, E. W. 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 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.



(Source, Lalpekhlua et al., 2024)

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

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).

Table-1- List of different vegetable taken numberofdaysfromplantingtomarketmaturityunderoptimumgrowing 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
Brusselssprouts[b]	90	–	100
Cabbage[b]	62	–	110
Carrots	60	–	85
Cauliflower,snowballtype[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,HoneyBall	–	105	–
Melon,HoneyDew	–	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	Podsarefilled,seedsimmature
Broccoli	Adequatediameter,compact,allfloretsshouldbeclosed
Cabbage	Firm head
Cantaloupe	¾ to full slip under slight pressure, abscission from vine
Carrot	Immature, roots reached adequate size
Cucumber	Immature and glossy skin
Garlic	Wellfilledbulbs,topsdrydown
Ginger	8–9 months after planting
Melon	Groundcolorchange towhitewithgreenishtint,slightly waxypeel
Mushroom	Capswell rounded,partial veilcompletely intact
Okra	Pod2–4″long,notfibrous,tipsofpodspliable
Onion (dry bulbs)	When10–20 % oftops fall over
Peas	Podswellfilledbutnotfadedincolor
Pepper	Fruitsize and color (depends on color and intended market)
Potatoes	Harvestbeforevinesdiecompletely,curetohealsurfacewounds
Radish (spring)	20–30 days after planting
Radish (winter)	45–70 days after planting
Tomato	Seedsfullydeveloped,gelformationadvancedinatleastonelocule

Watermelon	Flesh color 75 % red,TSS=10 %

(Source, El-Ramady, 2015)

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, A., and Harsha, S. P. 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 products for removal with excellent accuracy (Metcalfe, R. 2019). This system can handle large volumes within a short span of time with uniformity, thus saving manpower (Nama, 2022).

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

3.1.1Modified 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, S., and Goswami, T. K. 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, E. M. 2019).

Table-3-List of different vegetable and their benefits used underMA/CAstorage method.

Vegetable	Temperature	MA/CA	benefit

	(°C)	% O2	% CO2	
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, Kitinoja, L., & Kader, A. A. 2002).

3.1.2. 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 Systems

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, L. R., & Joshi, V. K. 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, C. G. 2015). This technique is suitable for high-value crops such as asparagus, broccoli, and peppers (Tyagi, S. K., and Khire, A. R. 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.

Table-4- Maximumstoragelife(days)innormalatmospherestorage(NA),controlledatmosphere (CA) and low-pressure storage (LP)

Commodity	**Maximum storage time (days)**		
	Normal atmosphere storage	**Controlled atmosphere**	**Low-pressure storage**
Asparagus	14–21	Slightbenefit–off-odors	28–42
Cucumber	9–14	14+(slight benefit)	49
Green pepper	14–21	Nobenefit	50
Lime (Persian)	14–28	Juice loss, peel thickens	90
Mango (Haden)	14–21	Nobenefit	42
Mushroom	5	6	21
Papaya(Solo)	12	12+(slight benefit)	28
Pear (Bartlett)	60	100	200
Protea (flower)	<7	Nobenefit	30
Rose (flower)	7–14	Nobenefit	42
Spinach	10–14	Slight benefit	50
Strawberry	7	7+(off-flavor)	21
Tomato (mature-green)	7–21	42	84

(Source, El-Ramady, 2015)

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.

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).

Table-5-Recommendedtemperatureandrelativehumidityforfruitsandvegetablesandthe approximate storage life under these conditions

Crop	Temperature(°C)	Relativehumidity(%)	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
Horseradish	−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)

3.6. Modular Storage Modules: Customizable modular units with compartments suited to the individual needs of the various vegetables are provided (Laufenberg, G., and Schulze, N. (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).

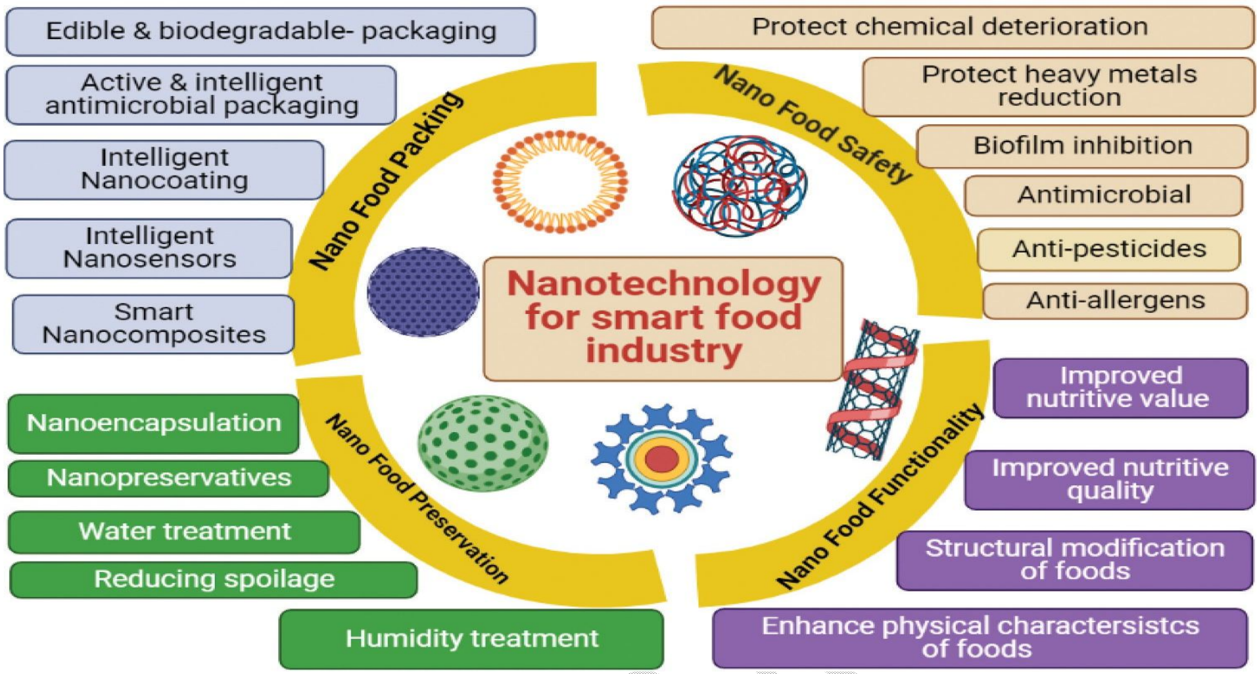
Table-6- Classificationofsomefruitsandvegetablesaccordingtoprincipalcausesofpostharvest losses and poor quality and in order of importance

Group	Examples	Principal causes of postharvest losses and poor quality (in order of importance)
Root vegetables	Carrots	Mechanical injuries
	Beets	Improper curing
	Onions	Sprouting and rooting
	Garlic	Waterloss(shriveling)
	Potato	Decay
	Sweet Potato	Chilling injury (subtropical and tropical root crops)
Leafy vegetables	Lettuce	Waterloss(wilting)
	Chard	Lossofgreencolor(yellowing)
	Spinach	Mechanical injuries
	Cabbage	Relativelyhighrespiration rates
	Green onions	Decay
Flowervegetables	Artichokes	Mechanical injuries
	Broccoli	Yellowingandotherdiscolorations
	Cauliflower	Abscissionofflorets
		Decay
Immature-fruit vegetables	Cucumbers	Over-maturityatharvest
	Squash	Waterloss(shriveling)
	Eggplant	Bruising and other mechanical injuries
	Peppers	Chilling injury
	Okra	Decay
	Snap beans	
Mature-fruit vegetables and fruits	Tomato	Bruising
	Melons	Over-ripenessandexcessivesofteningatharvest
	Citrus	Water loss
	Bananas	Chillinginjury(chillingsensitive fruits)
	Mangoes	Compositional changes
	Apples	Decay
	Grapes	
	Stone fruits	

(Source, Kitinoja, and Kader, 2002).

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).



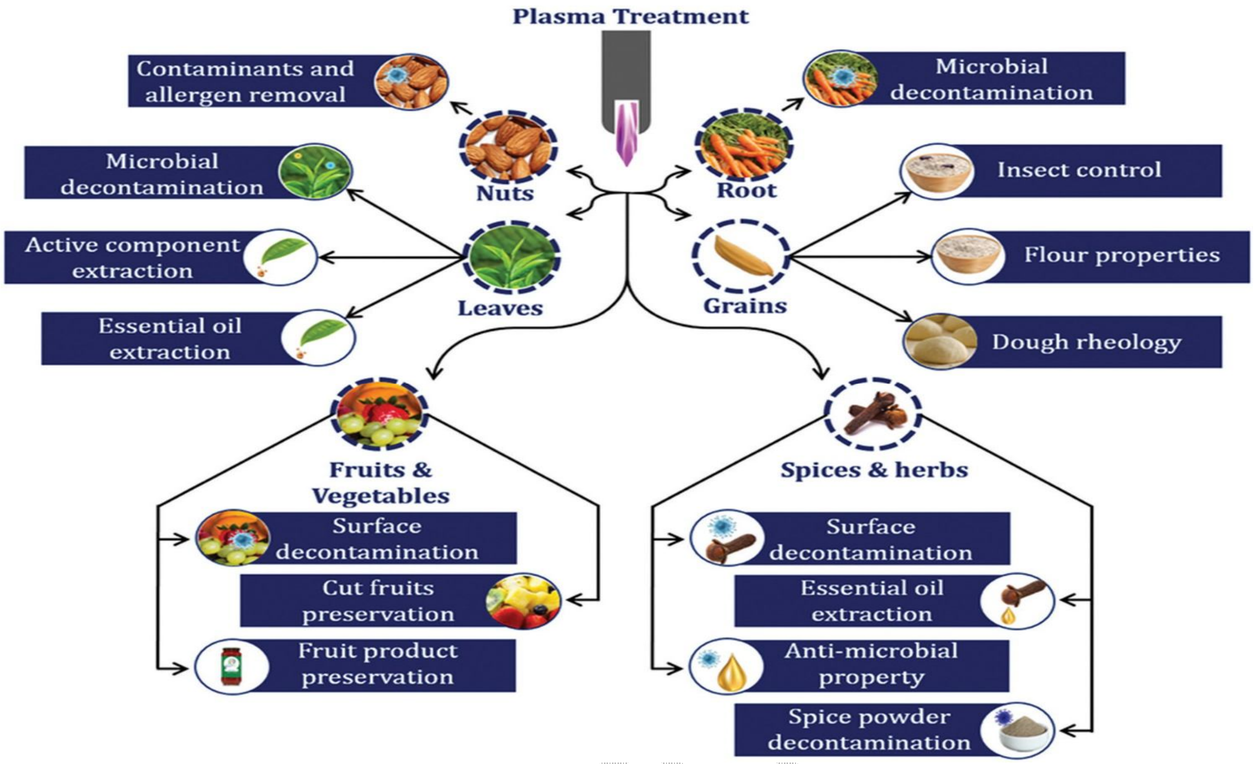
(Source, Lalpekhlua et al., 2024)

Figure 2. Various applications of nanotechnology for improving food packing, preservation, safety andfunctionality

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, K., and Kim, S. H. 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)**

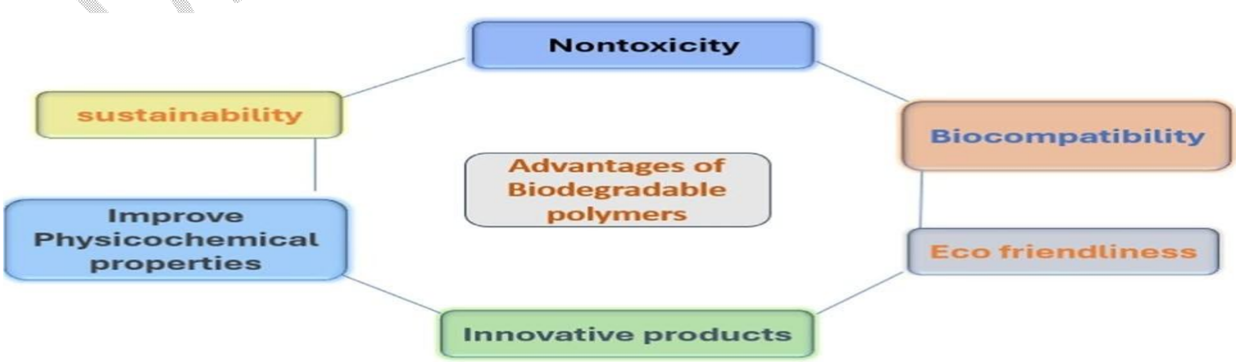


(Source, Lalpekhlua et al., 2024)

Figure 3. Pictorial representation of differentapplications andadvantages ofplasma treatment of various food crops including nuts, fruits, vegetables, grains, root vegetables, spices and herbs in thefoodindustry

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).

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).



(Source, Ali, et al, 2024)

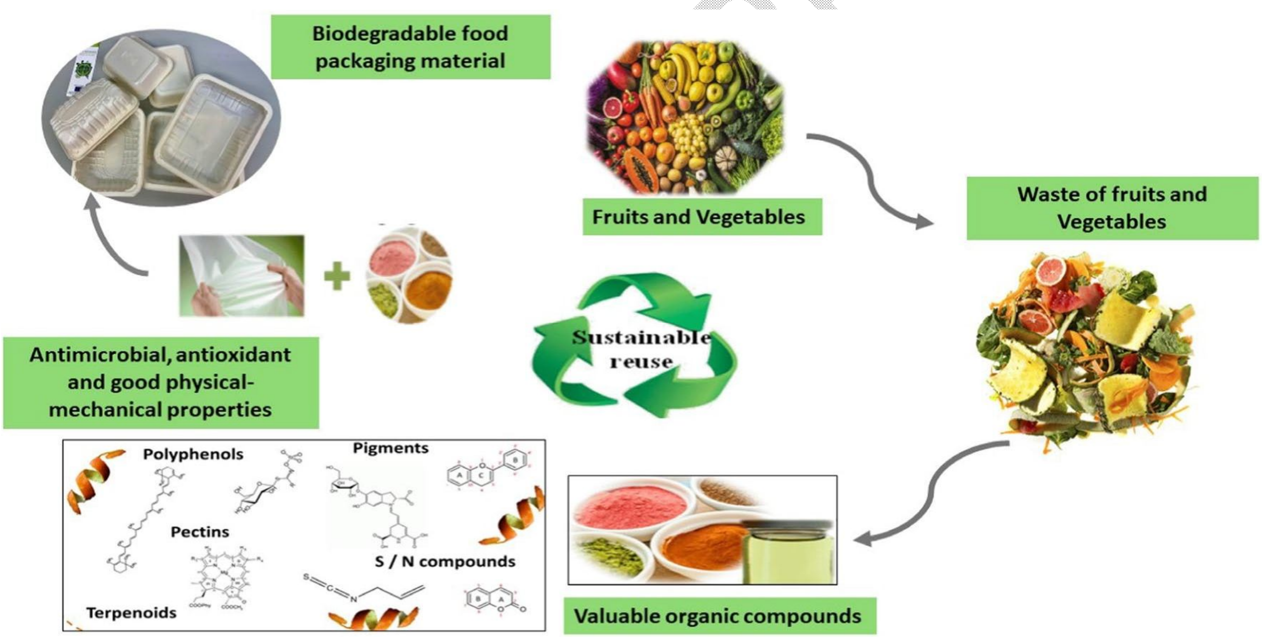
Figure 4. Showstheadvantages ofbiodegradablepolymers

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.



(Source, Ali et al., 2024)

Figure- 5- Biopolymers · Fruit and vegetable by-products · Biodegradable packaging · Edible films and coatings ·

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 (Kenyó, C. 2015). The antimicrobial agents kill microbes and also combat the action of free radicals which causes oxidative damage (Gavara R. 2015).

(Source, Ali, 2024)

Figure-6. Image of new active packaging

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).

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

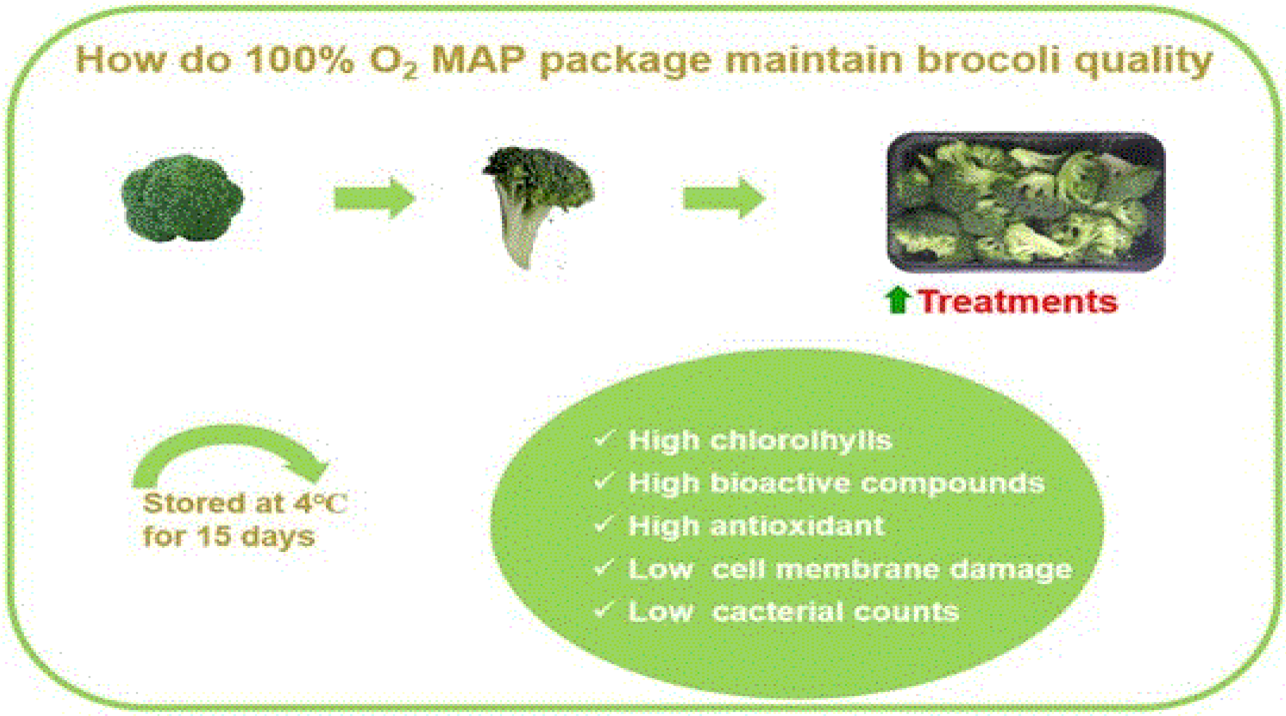
Natural polymers such as chitosan, alginate, and carrageenan are used to develop edible coatings that form a protective layer around vegetables (Tavassoli-Kafrani et al., 2016). These coatings minimize moisture loss, delay ripening, and reduce microbial spoilage (Salehi, F. 2020). Recent research has 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, R. N. 2003). Natural polymers such as chitosan and alginate have been utilized in creating edible coatings that prolong shelf life.

(Source, Gaspar, and Braga, 2023).

Figure-7. Image of edible coating packaging

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, et al., 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.



(Source, Dai, et al., 2023)

Figure-8- Image of broccoli stored by MAP.

5.4.1. Dynamic Gas Adjustment: Today advanced MAP systems come with dynamic features whereby oxygen (O□), carbon dioxide (CO□), and nitrogen (N□) levels should be regulated according to environmental changes and the respiration rate of packaged vegetables (Sebranek, J. G., and Houser, T. A. 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, P. J. 2022).

7. Sustainable Packaging Designs

Packaging solutions are now becoming lighter and reusable in a bid to minimize environmental impact (Marsh, K., and Bugusu, B. 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, T. M. 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, L., and Kader, A. A. 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, K. B. 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, G., and Zhang, H. 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, M., & Boks, C. 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.

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