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SMART TECHNOLOGICAL INNOVATIONS FOR POSTHARVEST LOSS REDUCTION: A REVIEW

*[1]Oyewole Omoniyi Samuel, [2]Raji Mariam Abiola, [3]Kazeem, Airat Alaba, [1]Ajao Taiwo Oluwatoyin, [2]Ibitoye Olufisayo, [2]Abel Omowunmi Olasumbo, [4]Solomon-Ibuwunwa Oluwakemi Mobolade, [1]Famakinwa John Olutobi and [5]Adewumi Elizabeth Olanike

[1]Postharvest Engineering Research Department, Nigerian Stored Products Research Institute, Ibadan, Nigeria.
[2]Durable Crops Research Department, Nigerian Stored Products Research Institute, Ibadan, Nigeria.
[3]Research Outreach Department, Nigerian Stored Products Research Institute, Ilorin, Nigeria.
[4] Perishable Crops Research Department, Nigerian Stored Products Research Institute, Ibadan, Nigeria.
[5]Research operation, Nigerian Stored Products Research Institute, Ibadan, Nigeria.

*Corresponding authors' email: oyewoleos@nspri.gov.ng; snoyeengrjnr@gmail.com

ABSTRACT

Postharvest losses remain a major threat to food security globally, particularly among low and middle-income countries where the losses of fruits and vegetables are over 30%. This study systematically examines recent technological innovations aimed at mitigating such losses along the postharvest supply chain. Drawing on a diverse range of empirical research, the review examines the performance of emerging technologies like plant-derived edible coatings, modified atmosphere packaging, solar-powered cold storage in mobile containers, evaporative cooling containers and hermetic dry chain systems. These technologies have demonstrated quantifiable gains in the shelf life, nutritional value and marketability of perishable agricultural produce. For instance, application of biodegradable coatings and films derived from essential oils has been associated with 40 to 70% reduction in microbial spoilage of fresh fruits and vegetables. Similarly, solar-powered evaporative coolers and on-the-go cold chain solutions have enhanced storage durations and reduced weight loss in leafy greens and tomatoes in off-grid rural locations. Yet, their successful implementation is usually hindered by systemic constraints such as farmers' lack of expertise, financial limitations and inadequate infrastructure. Field evidence highlights the necessity for context-specific design, farmer-centered training, and inclusive policy assistance. The research finds that optimal outcomes are achieved when smart technologies are implemented in conjunction with cooperative strategies that tackle behavioral, structural, and institutional issues. Propelling smart postharvest solutions will entail ongoing research, public-private partnerships and inclusive innovation pathways that accommodate the realities of smallholder producers.

Keywords: Food security, Technologies, Edible coatings, Cold storage

INTRODUCTION

The chronic issue of postharvest losses for fruit and vegetables is a profound inefficiency in global food systems with dire consequences for food security, nutrition and economic growth (Atanda *et al.,* 2011). In spite of several decades of research and a range of intervention possibilities, such losses continue to be undesirably high, especially among low- and middle-income countries (LMICs), where they can extend between 30% and 50% for perishables (Asare-Baah, 2023). These losses reduce available food supplies, lower farmer revenues, raise consumer prices and squander the substantial amount of resources used in production (water, energy, labor and agricultural inputs) (Kummu *et al.,* 2012).

The etiology of such postharvest losses is complicated and is multifactorial, taking place at numerous levels of the supply chain from harvesting to ultimate consumption. Mechanical injury during handling and harvesting, physiological breakdown, microbial spoilage, poor storage facilities and ineffective transport are all potential etiological factors (Kaur and Watson, 2024). In low- and middle-income countries (LMICs), these issues are frequently exacerbated by poor infrastructure, scarcity of technical expertise, low finances and disjointed market arrangements (Affognon *et al.,* 2015).

In the last decade, there have been dramatic changes in the way postharvest losses are reduced. There is increased acknowledgment that technologically advanced, capital-intensive interventions frequently don't work in resource-poor settings; conversely, appropriately scaled technology can yield huge gains if well implemented (Kitinoja and Barrett, 2015; Jarman *et al.,* 2023). Likewise, one can see a trend away from exclusively technological solutions toward comprehensive approaches incorporating human actions, market incentives and structural obstacles in addition to technical advances (Sheahan and Barrett, 2017).

This article presents trends in smart technological innovations for mitigating postharvest losses with an emphasis on ecologically friendly, economically sustainable, and contextually relevant technologies.

Key Technological Innovations

Plant-Based Compounds, Edible Coatings and Biofilms

Traditional postharvest disease control has largely been based on man-made fungicides and chemical control (Qadri *et al.,* 2020). However, growing concerns about environmental implications, public health and regulatory constraints have initiated a transition toward natural or plant-based alternatives (Chowdhury *et al.,* 2023; Ikhwani *et al.,* 2024). This transition also represents not merely a substitution of materials but an integral reassessment of preservation protocols.

Essential oils and extracts of plants are promising antimicrobial and antioxidant ingredients for postharvest use. Thyme, oregano, cinnamon, and citrus-derived chemicals, among others, have been reported to manage postharvest pathogens (Manzoor *et al.,* 2023; Rasheed *et al.,* 2024). Natural molecules have numerous benefits over synthetic ones, such as biodegradability, low toxicity, and greater consumer acceptance (Vurro *et al.,* 2019). Tabassum and Khan (2020) tested the efficacy of thyme and oregano essential oil-incorporated alginate-based edible coatings in the maintenance of quality in fresh-cut papaya. It was seen that these coatings, when applied and kept at 4°C, greatly extended shelf life through the minimization of water loss, retention of firmness, and improvement in microbial stability. Edible coatings and biofilms are another area of promise for postharvest conservation.

These coatings form semi-permeable barriers on the surfaces of fruits and vegetables that modify internal atmospheres, reduce moisture loss, and inhibit microbial growth (Sen and Singh, 2024). The bases of these coatings are materials such as chitosan (derived from the shells of crustaceans), alginate (derived from seaweed), various plant gums and cellulose derivatives, which can be further modified by incorporating antimicrobial agents, antioxidants, or texture-enhancing compounds (El-sayed and Youssef, 2024). Empirical experiments have proved that such natural methods can drastically increase shelf life without compromising product quality.

According to a study conducted by Guerreiro *et al.* (2015), alginate-based edible coatings, supplemented with essential oils, have been shown to enhance strawberry shelf life by as much as 50% when compared to untreated controls. Similarly, Khaliq *et al.* (2019) have demonstrated that dragon fruit gum Arabic coatings containing cinnamon oil effectively controlled anthracnose disease without affecting nutritional value. Silva *et al.* (2017) also investigated the role of chitosan coatings (0–3%) on postharvest quality of mango (Mangifera indica L. cv. Palmer) during storage at room temperature and found that chitosan delayed climacteric peak, reduced water loss, and maintained fruit firmness. Slight changes were observed in soluble solids, titratable acidity, pH, and sugar content, along with minimal starch breakdown, which reveals that chitosan coatings are effective in preserving mango quality by regulating respiration and carbon metabolism during storage.

Modified Atmosphere Packaging (MAP)

The development of Modified Atmosphere Packaging (MAP) has been extensive since its inception with recent innovations focusing on smart systems that respond adaptively to product and environmental factors. MAP technologies modify the levels of oxygen, carbon dioxide, and nitrogen present in the package to reduce respiration rates, inhibit ethylene production and inhibit microbial growth (Czerwiński *et al.,* 2021).

Some recent advances in MAP include the design of selectively permeable membranes, the incorporation of nanomaterials to improve barrier properties, the incorporation of ethylene absorbers, and the use of biosensors that monitor the conditions within packages (Idumah *et al.,* 2020; Bandyopadhyay and Ray, 2023). These enable more precise and adaptive atmosphere control and hence better efficiency under differing supply chain conditions. The prospects of MAP to reduce losses are significant. Wilson *et al.* (2019) demonstrated that MAP systems optimized reduced berry losses by up to 74% compared to conventional packaging. These benefits are, however, vitally dependent upon the modified atmosphere being maintained across the supply chain. Consumer behavior, for instance, can negate MAP performance; package opening early in use makes null and void the carefully established atmosphere, demonstrating the importance of consumer behavior and education to technology efficacy (Verghese *et al.,* 2015).

Ghidelli and Pérez-Gago (2018) conducted a comprehensive review of recent developments aimed at prolonging the shelf life of minimally processed fruits and vegetables using technologies such as modified atmosphere packaging (MAP) and edible coatings. The research identifies techniques such as MAP with low oxygen (O_2) and high carbon dioxide (CO_2) concentrations, antioxidant treatments, and edible coatings particularly those fortified with nanotechnology or multilayer systems as having great potential to minimize spoilage. Nevertheless, because of their high perishability, the use of more than one technology is usually required in order to provide both safety and long shelf life during distribution.

The sustainability considerations of MAP are increasingly becoming important. Plastic waste problems have prompted the search for biodegradable and compostable MAP products with functionality that can be maintained at lower environmental expenses (Yildirim *et al.,* 2018). These products represent an important step towards the alignment of loss reduction objectives with overall sustainability.

Cold Chain and Dry Chain Technologies

Temperature management remains fundamental to postharvest preservation, with appropriate cooling slowing metabolic processes and microbial growth in fresh produce. However, conventional cold chain systems often require substantial infrastructure and reliable electricity supplies that are unavailable in many rural areas of LMICs (Kitinoja *et al.,* 2011). Recent innovations have focused on making cold chain technologies more accessible, energy-efficient, and adaptable to diverse contexts. Solar-powered refrigeration systems offer promising alternatives for off-grid areas, with decreasing costs of photovoltaic technology improving economic viability (Dubey *et al.,* 2013). Phase-change materials that store thermal energy enable temperature stability without continuous power, addressing intermittency challenges in areas with unreliable electricity (Mvumi *et al.,* 2016).

Sibanda and Workneh (2020) examined the causes of postharvest losses in fruits and vegetables among small-scale farmers in sub-Saharan Africa. The study emphasized that high losses are mainly due to physiological deterioration caused by technical, biological, and environmental factors, as well as limited access to postharvest infrastructure. These losses negatively impact food security, income, and nutrition at the household level (Demshakwa *et al.,* 2023). The review explored the role of cold chain systems and assessed various cooling technologies. Although modern cooling methods exist, they are often unsuitable for small-scale farmers due to high costs and dependence on electricity. The Researchers proposed evaporative cooling as a more appropriate solution for these farmers, especially in hot and dry climates. The study recommended further research into the development or adaptation of solar or wind-powered evaporative cooling technologies for diverse climatic regions.

Bai *et al.* (2023) shed light on how smart cold chain systems can significantly help in cutting down global food waste, especially during the storage and distribution phases. They pointed out that around 20% of vegetables and 15% of fruits go to waste at the storage stage, with even more losses happening during distribution. The study took a closer look at traditional preservation methods and explored how cutting-edge technologies like sensors, wireless communication, the Internet of Things, blockchain, and digital twins can revolutionize cold chain logistics. These smart systems allow for improved monitoring, traceability, and control over environmental conditions, which is crucial for maintaining food quality. However, despite their advantages, challenges such as high costs and a lack of standardization are holding back broader adoption. Meanwhile, the study by Adesoye *et al.* (2024) examined a solar-powered evaporative cooling device tailored for small-scale farmers in rural areas. With many of these regions lacking electricity, the device was designed to help extend the shelf life of harvested crops, particularly tomatoes. It was tested over a week under both regular and controlled cooling conditions. The findings revealed that the cooling device managed to lower the average temperature with a saturation efficiency of 41%. Tomatoes kept in ambient conditions faced a hefty weight loss of 45.56%, while those stored in the evaporative cooler only lost 19.98% of their weight. The device maintained an ambient temperature between 23.03 and 26.08°C, along with a relative humidity range of 71.86 to 94.65%. This straightforward yet effective cooling system showed great promise in reducing postharvest losses, ultimately boosting the profitability of smallholder farmers. The authors concluded that such systems could be vital in enhancing food security and economic stability in rural farming communities. This study underscores the importance of affordable, renewable energy solutions like solar-powered evaporative cooling devices in tackling postharvest losses.

Ogunjirin *et al.* (2025) introduced a Mobile Solar-Powered Cooling System (MSCS) designed to be a sustainable way to keep perishable crops fresh in off-grid rural areas. This innovative system, which is mounted on a tricycle, features a 550-watt solar panel, a 150 ampere-hour deep-cycle battery, and a 75-watt DC compressor that uses isobutane (R600a) as a refrigerant. To test its effectiveness, the researchers used jute leaves. They found that the shelf life of these leaves increased from just four days in normal conditions to an impressive eleven days when stored in the MSCS. Additionally, weight loss was significantly reduced from 80% to only 8%, and vital nutrients like Vitamin A and beta carotene were preserved. Microbial analysis showed that the samples stored in the MSCS had a much lower microbial load compared to those kept at room temperature. The study concluded that maintaining a controlled low-temperature and high-humidity environment greatly enhances the shelf life and quality of jute leaves, suggesting that the MSCS could be a game-changer for vegetable supply chain stakeholders in off-grid regions.

When it comes to dry commodities like grains, nuts, and certain dried fruits, managing the "dry chain" is just as crucial. Some exciting innovations in this field include hermetic storage bags that create low-oxygen environments, budget-friendly moisture meters to help determine the best drying points, and enhanced solar dryers that not only keep products safe from contamination but also efficiently remove moisture (Bradford *et al.,* 2018). In their research, Bakhtavar and Afzal (2020) explored how Dry Chain Technology can help maintain the quality of quinoa seeds, emphasizing its role in food security. They looked into how drying quinoa seeds to various moisture levels (8%, 10%, 12%, and 14%) and storing them in either traditional packaging (like paper, polypropylene, cloth, and jute) or hermetic Super Bags over periods of 6, 12, and 18 months affected the seeds. The findings revealed that seeds kept in Super Bags at an initial moisture content of 8% retained low moisture levels and boasted higher germination rates, along with increased soluble sugars and α-amylase activity, while showing reduced levels of reducing sugars and MDA. On the flip side, seeds stored in conventional packaging absorbed moisture from their surroundings, leading to deterioration, as evidenced by higher reducing sugars, MDA levels, and decreased seed vigor and viability. The study concluded that Dry Chain Technology effectively prevents physiological and biochemical deterioration by keeping seed moisture low, ensuring quinoa seeds are stored safely.

Guzzon *et al.* (2020) explored how Dry Chain Technology can help with seed conservation in rural communities in Guatemala, where the high humidity and unreliable power supply make it tough to preserve seeds the traditional way. Their study focused on a local maize variety, comparing the Dry Chain method—which uses zeolite beads for drying and storing seeds in airtight containers—with the conventional seed conservation techniques found in community seed reserves and open storage. The findings revealed that seeds stored using the Dry Chain method kept their viability high (over 80%) and faced minimal fungal and insect infestations (less than 3%) over a six-month period. On the flip side, seeds stored using traditional methods in community reserves or open storage experienced a significant drop in viability, with around 52% becoming non-viable and 19% infested. This research highlighted that the Dry Chain method is a promising solution for enhancing seed conservation in tropical regions and bolstering seed security for farmers, particularly in areas with tough environmental challenges.

Baributsa and Ignacio (2020) highlight how smallholder farmers are increasingly turning to hermetic bags to tackle grain storage losses caused by pesky insects and the shortcomings of traditional storage methods. In the last 12 years, over 20 million hermetic bags—ranging from single to triple-layer plastic—have been sold, mainly across Africa and Asia. This rise in popularity is largely due to awareness campaigns, training programs, and better supply chains supported by the private sector. Hermetic bags come with a host of benefits, like keeping grain quality intact without relying on insecticides, allowing for storage periods of up to two years, and giving farmers the option to store both grain and seed. Plus, they can sell their grain at better prices when the market is right. Still, there are hurdles to overcome in boosting adoption, such as limited awareness and access in rural areas, inconsistencies in bag quality, and a lack of standardized criteria to ensure these bags work effectively for various products.

Poudel *et al.* (2020) explored grain storage techniques in the earthquake-affected Kavre district of Nepal, with a keen eye on reducing food waste in developing nations, where about a third of food goes to waste. This study, backed by UNICEF-Nepal, provided 1,055 households with storage bags that are pesticide-free, moisture-proof, and airtight. Out of these, thirty-three households took part in the experiment, storing maize and rice for six months in both porous and moisture-proof hermetic bags. The findings were striking: maize in porous bags faced a staggering 92% insect damage, while maize in triple-layer Purdue Improved Cowpea Storage (PICS) bags showed no signs of insect damage at all. On the other hand, rice stored in both types of bags experienced insect damage of less than 10%. The research also highlighted that insect damage resulted in considerable nutrient loss in maize, which is often used as animal feed when it becomes moldy. Additionally, mycotoxin levels were found to be higher in open storage, suggesting that harmful molds were developing, which further underscores the benefits of using airtight, moisture-proof storage solutions for better food security and nutrition.

Okonkwo *et al.* (2018) shine a light on the innovative work done by the Nigerian Stored Products Research Institute (NSPRI) with their Inert Atmosphere Metal Silo (IAMS). This groundbreaking technology is a game-changer for bulk grain storage, especially suited for Nigeria's unique climate. By utilizing nitrogen gas to create a controlled atmosphere (N_2-CA), IAMS effectively tackles pest infestations, curbs mold growth, and keeps the biochemical integrity of stored grains intact. Impressively, it has achieved a complete 100% mortality rate for all life stages of stored product pests while maintaining germinability rates between 85% and 91% over a year of storage. This system has been successfully employed to store a variety of grains, such as white maize, groundnut, cowpea, wheat, paddy rice, and sorghum, for durations ranging from 12 to 48 months. What's particularly noteworthy is that IAMS is the only system that can store cowpea, which traditional silos can't accommodate. Plus, it's proven to be cost-effective, boasting a return on investment of 0.44 for wheat storage over 48 months. IAMS also brings significant benefits over conventional silos by eliminating the need for regular pesticide applications and cutting down on labor costs. This technology has seen widespread adoption across communities in Nigeria, with smallholder farmers, entrepreneurs, and institutions like Landmark University, Federal University of Agriculture Abeokuta, University of Benin, among others for grain storage and research/teaching aids, ultimately enhancing food safety, quality, and nutrition.

Field trials across different settings have shown just how effective these technologies can be. For instance, Bradford *et al.* (2018) found that using dry chain management practices slashed postharvest losses in seeds and grains by as much as 98% in tropical areas. Meanwhile, Ambuko *et al.* (2017) discovered that affordable evaporative cooling chambers extended the marketable life of African indigenous vegetables by 2 to 5 days, which is a big deal for crops that spoil quickly. These innovations are especially beneficial for small-scale farmers and businesses in low- and middle-income countries, providing scalable solutions that can be gradually adopted as resources allow (Kitinoja *et al.,* 2011).

Small-Scale, Low-Cost Technologies

While cutting-edge technologies often steal the spotlight, it's the simpler innovations that can make a real difference when it comes to handling, packaging, and storage. These small-scale solutions prioritize accessibility, affordability, and fitting into local contexts over high-tech complexity (Kitinoja and Barrett, 2015). Jarman *et al.* (2023) point out that the advantages of agricultural innovations, especially in minimizing postharvest losses, aren't shared equally, particularly in low- and middle-income countries (LMICs) where small farms are prevalent. The high rates of postharvest losses in horticultural crops continue to be a significant hurdle. Their research showcases the promise of cold chain and dry chain technologies tailored for small-scale businesses, with real-world examples illustrating their positive effects.

Gouda and Duarte-Sierra (2024) delve into the issue of food loss and waste in the fresh fruit and vegetable supply chain, revealing that over 40% of losses happen globally, with developing nations facing substantial postharvest losses due to smallholders lacking access to modern technologies. On the flip side, developed countries mainly deal with waste at the retail and consumer levels. The study proposes affordable strategies like shading, low-cost packaging, and evaporative cooling for developing nations, while suggesting advanced technologies such as biosensors and imaging for the more developed regions. These methods aim to cut down on food loss, enhance storage solutions, and boost income for everyone involved in the supply chain.

Arah *et al.* (2015) point out just how vital tomato farming is for both nutrition and income, particularly for small-scale farmers in Africa. Yet, there's a significant hurdle: postharvest losses that cut into profits. These losses happen both on the farm and off, mainly due to poor road conditions, inadequate transport options, a lack of processing facilities, and limited access to market information. The study suggests that by embracing low-cost, intermediate technologies, farmers can greatly reduce these losses and enhance the economic sustainability of tomato production throughout the continent.

Verploegen *et al.* (2021) delve into the essential role of affordable postharvest storage in tackling fruit and vegetable losses in Rwanda and Burkina Faso, where spoilage takes a heavy toll on nutrition and farmers' earnings. In these areas, postharvest losses for tomatoes can hit between 50% and 60%, primarily because effective storage solutions are scarce in rural communities. The research shows that these budget-friendly cooling devices could be a game-changer, helping to prolong the shelf life of perishable goods and bolster food security.

Patel *et al.* (2022) delve into the postharvest storage hurdles that Indian farmers face, particularly the challenge of finding affordable cold storage options. Horticultural produce tends to spoil rapidly due to ongoing metabolic activity, especially in tropical climates. Although cold storage solutions are available, their high costs and energy requirements make them out of reach for many small-scale farmers. The study highlights evaporative cooling chambers (ECCs) as a cost-effective and eco-friendly alternative that can be built using locally sourced materials. However, despite their advantages, ECCs haven't seen widespread adoption in rural communities.

The economic argument for these technologies is quite strong. Kitinoja and Barrett (2015) discovered that small-scale postharvest technologies could yield returns on investment between 162% and 300% within a single season, making them a practical option even for farmers with limited resources. Additionally, these technologies can be introduced gradually, allowing farmers to invest progressively as they start to see the benefits.

Implementation Challenges and Barriers

Adoption and Accessibility

Despite the availability of effective technologies, their adoption is limited in many contexts, especially among small-scale producers in LMICs (Sheehan and Barrett, 2017). Many interconnected factors contribute to this implementation interval. Information barriers represent a significant obstacle, are unaware of the technologies available with many farmers and supply chain actors or lack specific knowledge about their benefits and implementation (Fognon *et al.,* 2015). This challenge has been extended by limited expansion services focused on post-class issues, as agriculture supports traditionally emphasizes production rather than production activities (kitinoja *et al.,* 2011).

Fauziana *et al.* (2023) present a thorough study about various determinants that affect postharvest loss reduction technology adoption by supply chain actors in West Java, Indonesia. The research combined structural equation modeling with qualitative interviews to show that farmers require knowledge and skills alongside infrastructure access and financial resources for implementing PHL technologies. The research indicates that supply chain actors require customized support programs and policy structures which address their distinct limitations and motivations through coordinated assistance programs and infrastructure development to enhance technology adoption while reducing financial losses. A systematic review by Bisheko and Rejikumar (2023) examined fundamental obstacles which prevent smallholder farmers in sub-Saharan Africa and South Asia from adopting advanced postharvest technologies. The research revealed that high expenses together with restricted availability of local resources and insufficient public knowledge represent the main challenges.

The research by Mutungi *et al.* (2023) demonstrates through strong empirical data how post-harvest technologies that are approved for use affect both food security and household welfare in Tanzanian maize-producing families. The analysis of survey information from 579 households demonstrates that farm size together with agro-ecological conditions and neighboring adoption play vital roles as adoption motivators. Airtight storage and group membership for tarpaulins as storage technology-specific enablers function alongside credit access and off-farm income opportunities. The implementation of the technologies led to substantial improvements in food availability and access alongside enhanced household income particularly through airtight storage which demonstrated the strongest benefits. The research found that adopting households dedicated less of their budget to food purchases which demonstrates their improved ability to withstand shocks and maintain food security. The study reveals that financial access combined with farmer knowledge sharing and group-based approaches play a vital role in expanding postharvest technology adoption throughout Africa.

Researchers led by Githumbi *et al.* (2024) conducted an investigation on how different factors affect the implementation of postharvest loss reduction methods in the Kenyan mango value chain. The research team examined the perspectives of farmers, wholesalers and retailers from Embu and Machakos and Nairobi counties. The study discovered that three main factors including availability of credit facilities together with increased losses and organized marketing created the most significant force for adoption. Farmers selected stick and bag methods while wholesalers showed preference for cartons and shades. The experience level of retailers directly affected their decision to use these practices. The study identified economic efficiency together with loss prevention and income growth as the primary incentives for change and it suggested implementing low-cost technology advancements for operational enhancement.

Constraints in funding present additional difficulties for implementation, specifically affecting technological solutions which demand initial capital expenditures. Resource-limited farmers face financial barriers to adopt even inexpensive innovations because they must wait for delayed benefits to develop (Bradford *et al.,* 2018). Many rural areas experience major financial limitations because of their lack of credit opportunities and banking services (Sheahan and Barrett, 2017). The adoption choices of individuals receive guidance from economic factors. The adoption of new technologies may experience poor economic support when producers sell products without quality distinctions or higher prices for better preserved items (Hodges *et al.,* 2011). The implementation of postharvest technologies becomes less attractive when market opportunities are unstable and risk is present (Affognon *et al.,* 2015).

Consumer Behavior

The effectiveness of postharvest technologies along with overall loss patterns depends strongly on consumer behavior in the supply chain. The benefits of MAP technologies disappear when consumers fail to handle products properly according to Verghese *et al.* (2015). Matar *et al.* (2020) conducted research which examined how Modified Atmosphere Packaging (MAP) reduced fresh strawberry postharvest losses. The research team developed a mathematical model that evaluated 132 storage conditions by accounting for both consumer habits and storage environments. The research demonstrated that MAP systems decreased loss levels by 17% but this reduced benefit occurred when 50% of consumers opened the packaging before placing the fruit in the refrigerator. The implementation of MAP in combination with proper consumer storage methods could lead to a 74% reduction in loss rates for strawberries. The research emphasizes how consumer actions determine the success of MAP implementation.

Cariappa *et al.* (2022) investigated the results of the COVID-19 lockdown on agricultural commodity prices, purchaser conduct, and food loss in India. They determined huge price will increase for chickpea, mung bean, and tomato, with tomato charges growing by using 78.2%, highlighting the loss of incredibly perishable items. Despite those charge spikes, the long-time period price traits lower back to pre-lockdown stages. The have a look at emphasizes the want for promoting small-scale manufacturing resilience via policies, virtual markets, and meals waste control practices to mitigate future shocks. Willersinn *et al.* (2017) analyzed six potential potato loss reduction eventualities in Switzerland, comparing their environmental, socio-economic, and customer sustainability using the "SustainOS" technique. While environmental upgrades from loss reduction were minimal, the socio-economic overall performance of the deliver chain confirmed substantial development. The look at found that patron alternatives were encouraged by perceived dangers, inconvenience, and attractiveness of loss-reducing measures. To address these behavioral dimensions requires a supplementary approach to technological innovation. Consumer education about proper handling and storage of fresh yield, campaigns promoting cosmetically incomplete items, and clear communication about innovative packaging can contribute to all consumer levels reduce losses at consumer levels (Varghese *et al.,* 2015).

Benefits and Future Directions

Economic and Food Security Gains

The capacity benefits of successful postharvest loss reduction are tremendous. Economic analyses advise that investments in postharvest technologies commonly yield returns of a hundred-250% over notably short intervals (Kitinoja and Barrett, 2015). These returns accrue via accelerated marketable yield, improved product fine, higher rate recognition, and extended advertising intervals. From a meals safety attitude, decreasing postharvest losses represents a vital approach for feeding developing populations without increasing agricultural land use. Hodges *et al.* (2011) anticipated that during sub-Saharan Africa, postharvest loss reduction ought to doubtlessly recover food equivalent to the caloric requirements of forty eight million people yearly. Balana *et al.* (2022) examine how adopting postharvest technology (PHT) affects earnings and livelihoods among perishable agricultural commodity sellers in Nigeria. Using econometric modeling, they observed that PHT adoption substantially boosts net returns and livelihood consequences. Counterfactual analysis indicates adopters would earn 7% much less without PHT, while non-adopters may want to advantage 5% greater in the event that they adopted. Key factors influencing adoption consist of earnings degree, era value, product seasonality, and position inside the deliver chain. The study highlights affordability as the primary barrier and calls for guidelines that enhance get admission to to low-fee technology and financing to reduce meals loss and enhance food security.

Mujuka *et al.* (2020) evaluated the economic benefits associated with investing in postharvest loss reduction technologies among Embu County's smallholder mango farmers in Kenya. Funded by the University of Nairobi and the Rockefeller Foundation's YieldWise Initiative, the research focused on enhancing two fruit aggregation centers using technologies such as tunnel solar driers, brick coolers, and cold storage. Based on the economic surplus model combined with cost-benefit analysis, the investment was determined to be feasible with a net present value (NPV) of US $1.3 billion, an internal rate of return (IRR) of 28%, and a benefit-cost ratio (BCR) of 4.29. Sensitivity analyses indicated that the investment is still feasible under less favorable macroeconomic conditions, emphasizing the need to promote these technologies to smallholder farmers.

Nutritive value is also critical. Fruit and vegetable crops are major sources of micronutrients, and their loss contributes to "hidden hunger" throughout much of the globe (Affognon *et al.,* 2015). Preservation of such nutritive value-rich crops through appropriate postharvest technologies can increase nutritional security along with caloric availability.

Focus on Education and Training

Sustained success in postharvest loss reduction rests squarely on human capacity building and technological advancement. The inclusion of postharvest management in agricultural education helps to rectify the previous focus on production topics. This way, future agriculture professionals will have useful knowledge (Kitinoja *et al.,* 2011). Establishing demonstration centers allows farmers to see and try out new technology, and this has worked in most instances. The Postharvest Education Foundation's idea of "Postharvest Training and Services Centers" offers practical training and creates local locations for technology exchange (Kitinoja and Barrett, 2015).

Building extension services that focus on postharvest matters helps to bridge the knowledge gap that could limit the adoption of new technology. Mobile extension services are a powerful way to reach rural areas at low cost (Ambuko *et al.,* 2017). Creating peer-to-peer learning networks takes advantage of farmers' preference to learn from trusted peers. Farmer field schools and local farmer demonstration plots have proven to be effective in spreading new technology (Bradford *et al.,* 2018).

CONCLUSION

The findings of this review indicate that smart technological innovations, especially with regard to storing and handling perishable crops such as vegetables and fruits, have immense potential in mitigating postharvest losses. Several studies show that some technological solutions, including edible coating, modified packaging, cold and dry storage facilities, and low-cost handling practices, keep food fresh for longer, maintain its nutritional value, and create value in the marketplace. Despite these advances, the study indicates significant challenges that render it difficult for additional individuals to employ such approaches, particularly small farmers in developing regions. They still have issues such as insufficient money, insufficient technical information, poor market incentives, and no specific training. The reviewed literature continually supports the view that postharvest loss reduction isn't totally a technical task however also a social and economic one. Efforts to scale up smart technological innovations must therefore be complemented by investments in schooling, infrastructure, and institutional capability. Establishing practical schooling facilities, strengthening extension offerings centered on postharvest issues, and selling farmer-to-farmer know-how change are vital for ensuring long-term adoption. Hence, the integration of smart technological solutions into local agricultural systems, whilst approached with attention to context and collaboration, gives a realistic pathway in the direction of lowering meals losses, improving livelihoods, and contributing to meals and nutritional safety.

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