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Review Article

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Technological Innovation and Advancement in Postharvest Management of Ginger (*Zingiber Officinale*): A Review

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ABSTRACT
This review explores technological advancements in the postharvest management of ginger (*Zingiber officinale*), a globally significant spice and medicinal crop. Renowned for its therapeutic properties, such as anti-inflammatory, antioxidant, and antimicrobial effects, ginger owes its medicinal value to over 400 bioactive compounds, including gingerol and shogaol. Despite its economic and medicinal importance, ginger faces significant postharvest challenges, including spoilage, weight loss, and quality deterioration. Traditional storage methods are often inadequate, resulting in substantial losses. However, advancements in technology have shown promise in extending shelf life and preserving quality. These include Controlled Atmospheric Storage, which regulates oxygen, carbon dioxide, and humidity levels to slow spoilage; Zero-energy Cool Chambers, which maintain high humidity and temperatures between 10-15°C, can reduce weight loss by up to 23%; Modified Atmosphere Packaging, which adjusts gas composition to inhibit microbial growth and oxidation; and cold storage, which minimizes sprouting at temperatures between 12-15°C and relative humidity of 70-75%. Additionally, natural preservatives like clove and thyme essential oils demonstrate antimicrobial efficacy, while nano-coatings improve moisture retention and pathogen resistance using biodegradable materials. Advanced techniques such as mechanized cleaning, ionizing radiation, pre-storage treatments, and coating methods using chitosan and beeswax also enhance post-harvest value of the crop. By integrating these technological advancements, the ginger industry can reduce waste, increase efficiency, and provide higher-quality products to consumers, ultimately improving this valuable crop's quality and shelf life.
Keywords: Ginger, Technological, Postharvest, Innovation, Storage

INTRODUCTION

The Zingiberaceae family comprises approximately 53 genera, encompassing over 1,200 species (Styawan *et al*., 2022). This family is primarily found in South and Southeast Asia. Among the plants in this family that are frequently utilized in herbal remedies are *Zingiber officinale* (ginger), *Zingiber zerumbet* (bitter ginger), and *Curcuma longa* (turmeric) (Koga *et al*., 2016). Ginger (*Zingiber officinale*) is a highly valued spice recognized for its culinary and health benefits, and economic importance. It is primarily produced in India, China, Nepal, Nigeria, Thailand, Indonesia, Bangladesh, Japan, and Cameroon (Maps of World, 2020). Syafitri et al. (2018) identified three primary types of ginger: Giant or white ginger (*Zingiber officinale* var. *Roscoe*), small white ginger or emprit ginger (*Zingiber officinale* var. *Amarum*), and red ginger (*Zingiber officinale* var. *Rubrum*). Globally, over 25 ginger varieties are cultivated, each differing in rhizome size, flavor, aroma, color, and fiber content (Shivakumar, 2020). From a medicinal standpoint, ginger is valued for its health-promoting properties, including anti-inflammatory, anti-diabetic, anti-obesity, antioxidant, and antimicrobial activities (Balogun et al., 2019). Clinical trials and molecular studies have confirmed its efficacy against ailments like nausea, diabetes, male infertility, and even SARS-CoV-2 (Unuofin *et al*., 2021). Modern pharmacological studies have identified over 400 bioactive compounds in ginger, including gingerol, shogaol, and zingerone, which contribute to its therapeutic properties such as anti-inflammatory, antioxidant, and antimicrobial effects (Mao *et al*., 2019; Shaukat *et al*., 2023). It offers various health-enhancing benefits and exhibits several pharmacological effects, including anticancer, antidiabetic, antioxidant, antimicrobial, and anti-neuroinflammatory properties, as well as effectiveness in alleviating chemotherapy-induced nausea and vomiting (Nile and Park, 2015; Zhu et al., 2018; Crichton et al., 2019; Mao et al., 2019).

Economically, ginger is a valuable commodity with substantial global production. In 2016, global ginger production was estimated at approximately 3.3 million tonnes (FAO, 2017). The leading ginger-producing countries include Nigeria, contributing 56.23% of the total, followed by India with 23.6%, China with 4.47%, Indonesia at 3.37%, and Bangladesh accounting for 2.32% (Tnau Agritech Portal, 2024). India ranks first concerning ginger production, contributing about 32.75% of the world's production, followed by China (21.41%), Nigeria (12.54%) and Bangladesh (10.80%), this contributed to its export market, which has experienced consistent growth in demand (Tnau Agritech Potal, 2024). According to experts from TMR 2022, the global valuation of ginger consumption was projected to reach $4.18 billion. This economic significance highlights its role as a dietary supplement and a driver of agricultural trade (Onwusiribe *et al*., 2018). In light of the foregoing, there is a growing global demand, which has resulted in increased production. The need for effective storage solutions to preserve its quality and extend shelf life. Traditional storage techniques, such as pit storage, bhaskari, and surface storage, as well as drying and bulk storage, are employed in regions like Nepal and Nigeria. Although packing rhizomes in PVC film can minimise weight loss, it can also elevate the risk of fungal infections (Ali *et al*., 2024). These conventional methods often result in significant spoilage, weight loss, sprouting, and quality deterioration, making a considerable portion of the stored crop unsuitable for consumption or sale. Storing rhizomes under optimum environmental conditions can extend their storage duration by minimizing weight loss and sprouting; however, this practice may increase the likelihood of pathogen invasion compared to room-temperature storage (Jingyi *et al*., 2021). The traditional methods for ginger storage have been handed down for generations, presenting certain advantages, including low cost and simplicity, while also facing major drawbacks, such as challenges in controlling temperature and humidity, limited shelf life, and susceptibility to pests, which impede the effective preservation of ginger rhizomes (Krüger *et al.*, 2018). As the demand for ginger increases, there is an urgent need to investigate and implement advanced storage technologies to improve the quality and shelf life of this valuable spice.

Kaushal *et al*. (2017) and Casimero *et al*. (2021) emphasize that ginger postharvest management faces significant challenges such as improper storage conditions, which can lead to spoilage due to microbial decay, weight loss through desiccation, sprouting at elevated temperatures, and quality degradation often caused by chilling injuries or mold growth. These issues are exacerbated by inadequate handling practices during harvesting and storage (Kaushal *et al*., 2017). For instance, rough handling can damage the rhizome's skin, increasing susceptibility to pathogens (Sagar, 2006; Kaushal *et al*., 2017). Furthermore, maintaining optimal storage conditions of ginger, such as temperature (12–15°C) and relative humidity (70–75%), is critical but often overlooked (Casimero *et al*., 2021). Chhetri *et al*. (2023) iterated that postharvest losses in ginger are significant due to poor handling techniques and a lack of technological interventions. These losses not only decrease the economic returns for producers but also reduce the availability of high-quality ginger for consumers (Abbas, 2018). Olusoga *et al*. (2016) reported that improper storage methods can lead to sprouting and nutritional degradation over time. Addressing these losses requires innovative approaches in postharvest management that integrate advanced technologies for preservation.

Therefore, it is pertinent to note that technological innovations in ginger storage and management will reduce the difficulties associated with traditional practices, ultimately benefiting both farmers and consumers. Yet, in the broader context of ginger storage, technological innovations that improve the shelf life of ginger are seldom researched or explored. This drawback informed the need for a systematic review that thoroughly examines technological innovation and advancement in ginger postharvest management. Given identify cutting-edge postharvest technologies that address key challenges in ginger preservation in the face of climate change dynamics.

Advances in Ginger Storage Technologies

Innovative storage technologies for ginger are designed to minimize spoilage and retain the active compounds within ginger (Jingyi *et al*., 2021). Controlled atmospheric storage involves managing oxygen, carbon dioxide, and humidity levels in the storage environment. It typically maintains an optimal temperature range of approximately 13–15°C and a relative humidity of 90–95%. This approach helps slow spoilage and sustain ginger's quality (Rahman *et al*., 2020). Zero-Energy Cool Chambers (ZECC) maintain a humidity level of 95% and temperatures between 10 and 15°C, reducing weight loss to approximately 23% after four months in storage, thereby significantly extending the shelf life of ginger. Modified atmosphere packaging (MAP) alters the gas composition around ginger during packaging, effectively reducing microbial growth and oxidation, resulting in a longer shelf life. Research by Khan *et al*. (2023) indicates that ginger packaged in modified atmospheres remains fresher and better retains its essential oils compared to those in standard packaging. Numerous studies have shown that cold storage can significantly enhance the viability of ginger tubers (Zhang *et al*., 2021). The incorporation of natural preservatives, such as essential oils, has gained attention due to their potential benefits. Oils derived from clove and thyme exhibit antimicrobial properties that can reduce spoilage and decay in stored ginger. The addition of these natural agents to storage treatments has shown promising results in maintaining ginger's quality (Kumar *et al*., 2022). The use of nano-coatings for ginger storage is an emerging field of study. These coatings can help manage moisture levels and limit exposure to pathogens while ensuring safety for consumption. Biodegradable nanomaterials have also proven effective in combating microbial growth in ginger (Ali *et al*., 2024).

Advancements in ginger storage and post-harvest handling technologies have significantly improved the quality and shelf life of ginger products. Here are some key developments:

Mechanised Cleaning and Sorting: Machines such as destoners, washers, and grading equipment are employed to eliminate soil, debris, and undersized rhizomes from harvested ginger, ensuring consistent quality and uniformity of the product (FAO, 2017).

Integrated Systems and Automation: Robotic and AI technologies are being integrated into planting and harvesting machinery to automate repetitive tasks, increase accuracy, and boost efficiency (Oliveira et al., 2021).

Pre-storage Treatments: Treatments like pit sawdust and storage methods have been found to improve sprouting rates, growth characteristics, and the quality of ginger rhizomes during storage (Villamor, 2012).

Modified Atmosphere Packaging: Packaging methods that control oxygen and carbon dioxide levels can help to prolong the storage life of ginger products (Elijah *et al.*, 2024).

Nano and Micro-sized Coatings: Coatings containing essential ginger oil and hydroxypropyl methylcellulose have been shown to preserve the quality and delay post-harvest decay of fruits like papaya (Oliveira *et al*., 2021).

Cold Storage: Maintaining a consistent refrigerated temperature can help slow down the aging process and extend the shelf life of ginger products (Anna *et al*., 2019).

Ionizing Radiation: Ionizing radiation can be used to disinfect and sterilize ginger products without adding chemicals, preserving nutrition and increasing quality and shelf life (Abdulkadir, 2019)

Overview of Coating Techniques in Ginger Preservation

Acevedo-Fani et al. (2017) highlighted that coatings can be created from a single substance or by combining multiple compounds through a layer-by-layer technique, resulting in multilayer coatings that perform reliably under various environmental conditions. A bilayer coating made of chitosan and carnauba wax has been applied to strawberries, where it effectively preserved firmness and minimized weight loss, as noted by Toliba et al. (2014). Similarly, Fan et al. (2019) emphasized that such coatings can slow the release of bound phenolics during storage, thereby maintaining higher phenolic levels over time. In a related context, Yousuf et al. (2018) explained that fresh ginger is typically stored using methods like modified or controlled atmosphere packaging, chemical preservatives such as color stabilizers or inorganic salts, refrigeration, and edible coating techniques, also widely used for preserving fruits and vegetables. Supporting this, Gol et al. (2013) confirmed that applying coatings to ginger helps retain its moisture, natural color, texture, and aroma.

Generally, Chitosan is a linear polysaccharide composed of glucosamine and N-acetylglucosamine units linked by α-1,4-glycosidic bonds. It is derived from the partial deacetylation of chitin, with the key difference between the two being the number of acetyl groups present in their molecular structures (Toliba et al., 2014). Chitosan is widely used in the development of biodegradable films and as a food preservative with antimicrobial properties. Its antibacterial activity is attributed to the presence of positively charged amine groups in its polymer chain. According to Toliba et al. (2014), chitosan helps extend the shelf life of fruits and vegetables by forming a barrier against moisture, oxygen, and carbon dioxide. Both chitosan and its derivative, oligochitosan, have been shown to reduce decay in stored ginger rhizomes by enhancing the activity of defence-related enzymes (Liu et al., 2016). When applied to plants, chitosan serves three primary roles: it triggers the plant's natural defence mechanisms, exhibits antimicrobial effects, and creates a protective film on the surface (Romanazzi et al., 2018).

Beeswax is a promising coating agent known for its ability to retain moisture and preserve the quality of rhizomes. Waxes are composed of esters formed from long-chain unsaturated fatty acids and long-chain monohydric alcohols or sterols (Kalscheuer et al., 2006). According to Rusmin et al. (2016), a study involving a 4% beeswax coating combined with 1,500 ppm of paclobutrazol effectively inhibited a significant proportion of sprouting in white ginger rhizomes stored at 20–22°C over three months. Devi et al. (2016) also observed that different storage methods significantly influenced the physicochemical characteristics of ginger, including pH, total soluble solids (TSS), total solids (TS), acidity, and water activity.

Chitosan and beeswax coatings form a protective layer over the stomata on the surface of ginger, effectively creating a barrier that slows down transpiration and respiration. Foo et al. (2019) demonstrated that a chitosan-beeswax coating helped minimise weight loss and microbial contamination in sapodilla fruits while preserving total soluble solids, firmness, and skin color. Similarly, Sultan et al. (2012) reported that Le Conte pears treated with a combination of chitosan, beeswax, and pollen grains showed significantly less weight loss than untreated samples. According to Harsha et al. (2015), the breakdown of polysaccharides into simpler sugars like monosaccharides and oligosaccharides contributes to an increase in total soluble solids (TSS). Their study further indicated that applying a coating of 3% chitosan and 6% beeswax to fresh ginger stored at 18°C helped slow the reduction of TSS, as well as the degradation of amino acids and antioxidants during storage

Fresh ginger should be kept in a cool, humid environment to preserve its quality. Ginger rhizomes are globally traded in both fresh and dried forms. From harvest to sale, proper storage conditions are essential to ensure they remain suitable for consumption (Devi et al., 2016). Harvesting ginger too early or too late can result in significant postharvest losses (Harmani et al., 2024). To minimize such losses, mature ginger rhizomes are typically recommended to be stored for 2 to 3 months at cooler temperatures between 12 and 14 °C, with a relative humidity (RH) of 85–90%, as this range helps reduce chilling injury and moistur loss (Jamal, 2010). Akamine (1977) reported that storing ginger at 13 °C with 65% RH caused dehydration and wilting of the rhizomes. During storage, ginger is susceptible to sprouting, mold development, physiological degradation, dehydration-induced shrivelling, and softening accompanied by discolouration (Yusof, 1990). Excessive humidity can promote sprouting, fibrous root growth, discolouration, and decay, which is why storage in polythene bags is discouraged (Afek and Kays, 2004). Due to the high costs of maintaining the necessary storage conditions, farmers often store ginger rhizomes in underground tunnels or sand. In these environments, temperature and relative humidity (RH) can be controlled, but they must be closely monitored to prevent significant losses (Kim and Lee, 2006). Ginger rhizomes are sensitive to chilling, which can lead to skin pitting and color changes (Yi, 2017). Sprouting during storage is a common issue; however, moderate doses of ionizing radiation (such as gamma or X-rays) have been found effective in suppressing sprout development (Mukherjee et al., 1995; Yusof, 1990). According to Chung et al. (2011), storing ginger rhizomes in perforated low-density polyethylene (LDPE) bags helps reduce rotting while maintaining their color, firmness, pH, and overall sensory quality (Chung and Moon, 2011)

Impact of Storage Conditions on Ginger Quality

Ginger quality is greatly affected by storage conditions, particularly in terms of maintaining its bioactive components. One of the most important components of ginger is 6-gingerol, a bioactive substance having anti-inflammatory, anti-cancer, and antioxidant properties. Inadequate storage and postharvest handling might lead to deterioration, hence decreasing the value of ginger

Phytochemical Stability of Ginger

Ghasemzadeh *et al.* (2016) showed that sealed glass containers are more effective in preserving 6-gingerol compared to plastic or unsealed containers. The impermeability of glass to moisture and gases helps maintain the chemical stability of ginger. On the other hand, plastic containers may allow for slight oxygen permeability, which accelerates the degradation of bioactive compounds. Additionally, unsealed containers expose ginger to air, leading to oxidation and loss of phytochemical potency (Shukor *et al*., 2020). Temperature and humidity also play significant roles in ginger's phytochemical stability. For example, low-temperature storage (4°C) has been reported to better retain 6-gingerol content than ambient or high-temperature storage. Controlled humidity levels further mitigate the degradation process, preventing mold growth and moisture-induced breakdown (Ghasemzadeh *et al*., 2016). In a Nigerian study, ginger kept in sealed glass containers under controlled conditions retained more than 80% of its 6-gingerol content after three months, while ginger kept in plastic containers only retained 50%. Similar results have been reported abroad, where ginger kept at 5°C maintained its antibacterial and antioxidant qualities for up to four months (Shukor *et al*., 2020).

Germination and Sprouting Control in ginger

Germination and sprouting have a major effect on the quality and shelf life of preserved ginger. Rhizomes of ginger seeds kept in Zero Energy Cool Chambers displayed notable morphological alterations (Borah and Shaikia, 2020). Weight loss reached 28% after three months of storage. The number of sprouting buds increased to 12.25 during this period. Bud dimensions varied, with length increasing and breadth decreasing over time (Kirankumar 2001). Histochemical studies revealed changes in cork layers, starch grain size, and oil globules. Understanding these changes can inform strategies for controlling germination and sprouting in stored ginger (Chittaragi *et al*. 2022). Ginger rhizomes are susceptible to damage during postharvest storage; such storage methods significantly impact sprouting, weight loss, and nutritional quality. For instance, Olusoga *et al.* (2023) reported the highest sprouting percentage (94.90%) in pit-sawdust storage, clay pot storage resulted in the least weight loss (27.89%), and maintained nutritional quality. Refrigerator storage resulted in the highest weight loss (62.78%) and lowest sprouting percentage (66.28%). Optimal storage methods can maintain ginger quality and promote better growth. Good preservation practices can reduce losses and maintain the therapeutic benefits of ginger. Maintaining ginger's market value also requires proper preservation. By managing weight loss and sprouting, growers may boost crop yields. Food security and economic expansion may benefit from this (Olusoga *et al*. 2023).

Socioeconomic implications of innovation in ginger handling

Considerable socioeconomic implications of innovation in ginger handling include: Income enhancement: the adoption of advanced processing technologies has significantly boosted farmers' income by reducing losses and improving product quality (Sati and Bala 2017). In Enugu State, Nigeria, the use of ginger production technologies led to increased productivity and income for rural households, as affirmed by (Ukamaka and Eberechukwu 2018). Employment Opportunities: the establishment of processing centers and training programs has created jobs for local youths in regions like Mizoram according to (Sati and Bala 2017).

Olaghere *et al* (2022) confirms that farmers, processors, and marketers making large profits, in the ginger value chain and had enormous economic potential. Olaghere *et al* (2022) relates research conducted in Kaduna state, Nigeria, pointed out producer's net margins are 140,000 NGN/ha/year, processors' net margins are 3,300 NGN/bag, and marketers' net margins are 3,470 NGN/bag in tandem to profitability indexes, processors made the most money, with a 70% profit margin. The profitability of processors differed statistically from that of other players, according to a comparative study. The study highlights the need for policies to encourage ginger production, processing, and marketing, with a focus on processing. Nigeria's ginger's worth and competitiveness in global markets may be improved by creating regulations to encourage value-added procedures, grading schemes, and training initiatives. The ginger value chain in Nigeria offers significant economic potential, with opportunities for expansion and growth. Nwaekpe *et al*. (2019). Findings from a study conducted in Abia State, Nigeria, reported a rapid value chain to identify areas for improvement and enhancement. The analysis revealed a basic and transactional relationship among chain actors, lacking trust and effective information flow. By minimizing post-harvest losses, enhancing processing and marketing procedures, and boosting revenues through value-added operations, the ginger value chain may help smallholder farmers. Adoption of cutting-edge technology is still difficult, nevertheless, due to factors including cold storage facility costs and the requirement for scalable, reasonably priced solutions (Nwaekpe *et al.*, 2019). Policies supporting the ginger value chain can contribute to economic growth, poverty reduction, and improved livelihoods for smallholder farmers. Hence, analyzing the ginger value chain using a rapid value-chain assessment method can offer valuable insights for designing inclusive interventions aimed at enhancing the overall efficiency and effectiveness of the chain (Nwaekpe et al., 2019).

On the other hand, ginger production faces numerous challenges, including susceptibility to diseases, fluctuating market prices, and, critically, significant postharvest losses (PHLs). These losses occur at various stages of the value chain, from harvesting and handling to storage, transportation, and processing. Here are some notable challenges

Limited Technology Adoption: Despite awareness, utilization of advanced ginger processing technologies remains low in some regions due to socioeconomic factors like education levels and cooperative membership (Makarau *et al*., 2013).

Market Access Challenges: Poor postharvest handling practices and lack of market access have constrained farmers' ability to benefit from ginger production despite its economic potential across developing countries (Sati and Bala 2017).

Infrastructure Deficiencies: Lack of proper storage facilities and processing equipment continues to hinder ginger production in areas like Ethiopia's SNNPRS region (Getacher *et al.*, 2013).

Market Price Volatility: Cyclical variations in product prices due to inconsistent quality remain a challenge for farmers in developing regions (Prasad and Tyagi 2015).

Causes of Postharvest Losses in Ginger

Ginger PHLs are attributed to a combination of factors, including:

Biological Deterioration: Fungal and bacterial infections, sprouting, and physiological changes lead to weight loss, quality degradation, and reduced market value (Laelago *et al*., 2023). Inadequate Handling and Storage: Poor harvesting practices, improper curing, and insufficient storage facilities contribute to bruising, damage, and accelerated spoilage (Kaushal *et al*., 2017). Inefficient Transportation: Long distances to markets, inadequate packaging, and lack of refrigerated transport systems exacerbate losses, particularly in developing countries (Singh, 2013). Limited Processing Capacity: Lack of accessible processing facilities limits the conversion of fresh ginger into value-added products, contributing to spoilage during peak seasons (Datta *et al*., 2015).

Strategies for Reducing Postharvest Losses in Ginger:

The Technologies and Practices innovated to reduce postharvest losses in ginger include:

Improved Harvesting and Handling Techniques: This examines improved harvesting techniques that minimize physical damage to ginger rhizomes, such as harvesting at optimal maturity and using appropriate tools. It will also explore best practices for handling ginger after harvest, including sorting, cleaning, and grading (Nwaekpe, *et al*., 2022).

Enhanced Curing and Drying Methods: Curing and drying are critical steps in postharvest handling. This section explores the use of improved curing methods, such as forced-air ventilation, and drying techniques, such as solar drying and controlled-temperature drying, to reduce moisture content and prevent spoilage (Sharma *et al.*, 2018).

Advanced Storage Technologies: This section examines advanced storage technologies, including controlled atmosphere (CA) storage and modified atmosphere packaging (MAP), which can extend the shelf life of ginger by regulating oxygen and carbon dioxide levels (Yahia, 2009). The feasibility and cost-effectiveness of these technologies for smallholder farmers will be assessed.

Innovative Packaging and Transportation Solutions: This section explores the use of improved packaging materials, such as ventilated bags and refrigerated containers, to protect ginger during transportation and reduce physical damage and spoilage (Singh and Singh, 2019).

Processing and Value Addition: This section examines opportunities for processing ginger into value-added products, such as ginger powder, ginger oil, ginger candy, and ginger extracts, to reduce postharvest losses and increase farmer income (Ravindran and Babu, 2007). The economic viability and market potential of these products will be analyzed.

The Role of Digital Technologies: This section discusses the potential of digital technologies, such as mobile apps and online platforms, to improve information sharing, market access, and supply chain management in ginger production (Babu *et al*., 2024).

Future Direction for Ginger Handling

Sustainable Practices require the continued adoption of eco-friendly technologies like SiNPs, which can enhance ginger quality while reducing environmental contamination from chemical fungicides. Expansion of Processing Centers: Scaling up postharvest processing centers globally can reduce losses and improve market competitiveness for smallholder farmers.

Innovative Preservation Techniques for Extending the Shelf Life of Ginger

Modified Atmosphere Packaging (MAP): Exploration of the application of MAP for ginger preservation, including the optimization of gas compositions (O_2, CO_2, N_2) to reduce respiration rate and microbial growth. Consideration of different packaging materials and their permeation properties. (United Nation Development Project, 2016).

Edible Coatings: Review of the use of edible coatings based on natural polymers (e.g., chitosan, starch, cellulose) to create a protective barrier against moisture loss, oxygen diffusion, and microbial contamination. Incorporation of antimicrobial agents into edible coatings. (Prasad and Tyagi, 2015)

Irradiation: Discussion of the potential of irradiation as a postharvest treatment to control sprouting and microbial spoilage. Addressing consumer concerns regarding food safety and the need for proper labeling (Reddy *et al*., 2018)

Plant-Based Antimicrobials: Investigation into the use of plant-derived essential oils and extracts as natural preservatives to inhibit microbial growth in ginger. Focus on essential oils with proven antimicrobial activity, such as clove oil, thyme oil, and cinnamon oil. NRCRI (2015).

Emerging Technologies: Cold Plasma and Ozone Treatment: Exploration of the application of novel technologies like cold plasma and ozone treatment for surface disinfection and extending shelf life. (Misra *et al*, 2016)

Sustainable Packaging and Storage Solutions for Ginger

The Importance of Sustainable Packaging: Discussion of the environmental impact of traditional packaging materials and the need for sustainable alternatives. Biodegradable and Compostable Packaging: Exploration of the use of biodegradable and compostable packaging materials derived from renewable resources, such as plant fibers, starch, and polylactic acid (PLA). (Mohanty *et al*., 2002). More so, Recycled and Recyclable Packaging: Review of the use of recycled and recyclable packaging materials, such as recycled paperboard and polyethylene terephthalate (PET).

Optimized Storage **Conditions:** Detailed discussion of the optimal temperature, humidity, and ventilation requirements for ginger storage. Consideration of different storage systems, including (Jamal, 2010)

Controlled Atmosphere (CA) Storage: Maintaining specific levels of oxygen, carbon dioxide, and ethylene to slow down respiration and senescence (Thompson *et al*., 2028).

Cool Storage: Refrigerated storage to reduce metabolic activity and microbial growth.

Evaporative Cooling: Using evaporative cooling techniques to maintain lower temperatures and higher humidity in storage facilities. Energy-Efficient Storage Systems: Exploration of energy-efficient cooling and ventilation systems for reducing the environmental footprint of ginger storage facilities. Use of renewable energy sources (e.g., solar power) to power storage systems (Kumar *et al*., 2018).

Digital Technologies for Traceability and Supply Chain Management of Ginger

The Need for Traceability in the Ginger Supply Chain: Discussion of the importance of traceability for ensuring food safety, quality, and authenticity. Blockchain Technology: Exploration of the application of blockchain technology for creating a transparent and secure record of ginger production, processing, and distribution. Enhancing consumer trust and enabling efficient recall management. (Kshetri, 2018). Internet of Things (IoT) Sensors: Review of the use of IoT sensors to monitor temperature, humidity, and other environmental conditions throughout the supply chain. Real-time data collection and analysis for optimizing storage and transportation. (Atzori *et al*., 2010). Mobile Applications: Development of mobile applications for farmers and processors to record information on ginger production, quality, and inventory. Improving communication and coordination among stakeholders in the supply chain (Moyo, 2024). Data Analytics and Predictive Modeling: Using data analytics to identify patterns and predict potential risks in the ginger supply chain. Optimizing logistics, reducing waste, and improving efficiency (Arowosegbe *et al*., 2024)

CNCLUSION

Postharvest losses in ginger pose a significant threat to food security, economic development, and rural livelihoods. Addressing these losses is vital for sustainable agricultural development and improving farmers' livelihoods. This review highlights the importance of technological advancements in managing postharvest challenges in ginger (*Zingiber officinale*), such as spoilage, weight loss, and quality deterioration. Traditional storage methods, while cost-effective, often lack proper temperature and humidity control, leading to losses. Innovative solutions like controlled atmospheric storage, Zero-Energy Cool Chambers (ZECC), modified atmosphere packaging (MAP), and natural preservatives such as essential oils have proven effective in extending ginger's shelf life. Additionally, coating techniques using chitosan and beeswax can reduce microbial infection and moisture loss. Methods like mechanized cleaning and ionizing radiation for sprout inhibition can enhance postharvest outcomes. However, economic constraints and accessibility challenges limit the adoption of these technologies. Therefore, integrating tailored advanced postharvest solutions is essential for reducing losses, boosting producers' economic returns, and ensuring high-quality ginger in global markets. Continued research and innovative storage solutions are needed to meet the growing demand for ginger while addressing sustainability concerns.

CONFLICT OF INTEREST

The author here declares that there is no conflict of interest in the publication of this article.

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