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REVIEW PAPER

SAFETY AND SHELF LIFE OF MINIMALLY PROCESSED FRUITS AND VEGETABLES: ADVANCES IN PACKAGING, AI MONITORING, AND CONSUMER PRACTICES

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Abstract

Consumer demand for convenient, fresh-like, and minimally processed foods has increased substantially in recent years fuelled by rumours, fear of additives and distrust in processed foods. Although minimally processed fruits and vegetables (MPFV) retain most of the nutritional and sensory qualities of fresh produce, they are susceptible to microbial growth due to the absence of a thermal or kill processing step. This article provides an overview of the major safety challenges associated with MPFV and explores emerging technological solutions to mitigate these risks. Key topics include microbial and environmental hazards across production, post-harvest and processing stages. Innovations in smart and active packaging, artificial intelligence (AI) applications for quality monitoring and shelf life prediction are described, together with the importance of consumer education in improving food safety outcomes. By integrating technological innovation with informed consumer practices, the food industry could better ensure the microbiological safety, and sustainability of MPFV products.

Keywords: minimally processed, food safety, shelf life, consumer education, risk communication

Introduction

In recent decades, consumer preferences have shifted toward fresh-like, convenient, and “clean label” foods obtained by minimal processing. Minimally processed products are foods that undergo limited or mild preservation treatments to maintain the natural attributes of raw materials (Gil *et al*., 2015), such as mild heat treatments, high-pressure processing, pulsed electric fields, solely or in combination with several hurdles like antimicrobials, active packaging, cold chain, to achieve food safety objectives meant to protect consumers` health. These

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products are perceived as healthier alternatives to conventionally-processed foods as they retain most of their nutritional and sensory characteristics, whereas conventional processing technologies often result in greater losses of bioactive compounds (Asioli *et al*., 2017). However, the same factors that enhance consumer appeal - limited preservatives, mild processing, and short distribution chains - also increase susceptibility to microbial, chemical, and physical hazards.

Minimally processed fruits and vegetables (MPFV) have emerged as a dynamic and rapidly growing sector within the fresh produce industry. Marketed under various forms - such as fresh-cut, pre-cut, or ready-to-eat items - these products appeal to modern consumers seeking convenience, freshness, and reduced preparation time (Silveira *et al*., 2022). However, unlike thermally processed foods, MPFV do not undergo a target lethal step for pathogenic microorganisms' inactivation, like pasteurization or sterilization, which significantly increases their susceptibility to microbial growth (Kim and Cheigh, 2021). Moreover, the fresh products' biological nature and their multiple handling steps can lead to their frequent contamination with major food pathogens due to their sensitivity, despite the combination of hurdles that are designed for reducing the presence of pathogens. Thus, the fresh and MPFV could become more easily contaminated than conventionally processed ones with bacterial strains as *Listeria monocytogenes*, *Campylobacter* spp., *Salmonella* spp., *Escherichia coli* O157:H7, *Cryptosporidium* spp. or with viral spp. as Norovirus or Hepatitis A (Kroft *et al*., 2022; Grivokostopoulos *et al.*, 2022; Tenea *et al*., 2024; Balali *et al*., 2020). More worryingly, according to a recent European Centre for Disease Prevention and Control report (2024), foods of vegetal origin, in particular 'vegetables and other products thereof', caused the largest number of deaths in strong- evidence outbreaks.

The microbiological quality of raw materials is determined mainly by pre-harvest factors such as soil, irrigation water, and environmental conditions. Pathogens such as *E. coli* O157:H7, *Salmonella spp.*, and *Listeria monocytogenes* have been detected in soil and water used in vegetable cultivation (Iwu and Okoh, 2019; Alegbeleye *et al*., 2018). Soil contamination may arise from the application of untreated manure, the use of contaminated organic fertilizers, or runoffs from nearby animal operations. Water quality plays a crucial role in both irrigation and post-harvest washing steps. Depending on the source (surface, ground, or reclaimed water), irrigation water can serve as a vector for enteric pathogens transmission (Pachepsky *et al.*, 2011, Iwu and Okoh, 2019). It was demonstrated that sprinklers and surface irrigation systems pose higher risks of microbial transfer to edible plant tissues compared to drip systems (Iwu and Okoh, 2019). Climatic variables such as temperature, humidity, and rainfall patterns further influence the prevalence and persistence of foodborne pathogens in agricultural environments (Singh et al. 2023). Increased average temperatures and extreme weather events linked to climate change can alter microbial survival rates and facilitate contamination through water runoff or flooding (Misiou and Koutsoumanis, 2022; Singh *et al*., 2023). Although microbiological hazards are the most prominent for human health, fruit and vegetables may also be exposed to chemical and physical risks. Pesticide residues, heavy metals, and mycotoxins can be present due to improper agricultural practices or environmental contamination (Gottardi *et al.*, 2021).

Post-harvest processing and subsequent distribution stages introduce additional opportunities for microbial contamination. Mechanical operations such as cutting and peeling compromise fruits' and vegetables' natural barriers make them more prone to contamination events. Therefore, rigorous hygiene practices, microbiological quality of wash water, equipment sanitation, and personnel handling practices are critical to reducing contamination risks (Castro-Ibáñez *et al*., 2017). Researchers have demonstrated that inadequately designed or insufficiently cleaned processing surfaces, including conveyor belts and shredding equipment, may act as reservoirs for certain pathogens: *Listeria monocytogenes*, *Escherichia coli*, and *Salmonella* spp. (Buchholz *et al*., 2012). Likewise, poor hand hygiene among food handlers has been identified as a direct source of contamination i.e. *Staphylococcus aureus* (Colombari *et al*., 2007).

Temperature management during storage, transport, and retail remains one of the most critical factors for maintaining both quality and safety, as temperature fluctuations are common during transportation, storage, retail display and consumer handling. Studies have shown that temperature abuse events-such as prolonged exposure to ambient conditions in supermarkets can drastically reduce product shelf life and safety because they facilitate the growth of pathogens, even at refrigeration levels (Kotzekidou, 2013; Zeng *et al*., 2014). Brief deviations above like 8-10°C during storage or transport can significantly accelerate microbial growth (Zeng *et al*., 2014). Many psychrotrophic pathogens, including *L. monocytogenes*, can grow at refrigeration temperatures (Kotzekidou, 2013).

Household settings were frequently reported places of exposure, associated with food-borne outbreaks (Borda *et al*., 2020).

At consumer level, contamination of MPFV is primarily associated with unsafe handling practices. These include improper storage and refrigeration practices (e.g., temperature abuse, incorrect placement in the refrigerator), inadequate washing of fruits and vegetables (e.g., poor water quality, inappropriate washing temperature, insufficient use of cleaning agents), poor personal hygiene (e.g., handling food with unclean hands), and cross-contamination (e.g., contact with contaminated cutting boards, utensils, or hands).

Thus, ensuring the safety of MPFV requires a holistic approach encompassing good agricultural practices (GAP), as well as good manufacturing practices (GMP), technological hurdles, together with innovative packaging and modern technologies for safety monitoring. This article aims to present the key technological advancements as smart packaging and the use of artificial intelligence and discuss the importance of consumer education in ensuring safe handling and consumption of MPFV.

Packaging innovations promoting food safety and shelf life extension

The packaging of MPFV plays a critical role in preserving freshness, maintaining safety, and extending shelf life. Because MPFVs are highly perishable and often stored under refrigeration conditions, packaging systems must create optimal conditions that minimize physiological degradation and microbial proliferation while ensuring product integrity throughout the supply chain (Han, 2014). In recent years, research has increasingly focused on smart packaging systems like active and intelligent packaging that went beyond the traditional passive barrier function of conventional materials.

Active packaging systems

Active packaging systems are designed to extend shelf life by actively modifying the internal atmosphere or interacting with the product to maintain quality. They may contain components that absorb or release substances such as gases, moisture, or antimicrobial agents (de Oliveira Filho *et al*., 2021). Common examples include oxygen scavengers, ethylene absorbers, moisture regulators, and antimicrobial films. Active oxygen scavenging systems are typically commercialized as sachets, labels, or films containing reactive compounds that remove residual oxygen within the package headspace. The most common formulations include iron-based powders, ascorbic acid, sulfites, photosensitive dyes, or enzyme-based systems capable of reacting with oxygen to form stable oxidation products (Ahmed *et al*., 2022; Gaikwad and Lee, 2017). In the context of fresh fruits and vegetables, oxygen scavengers are particularly effective in slowing enzymatic browning, chlorophyll degradation, lipid oxidation, and aerobic microbial growth which notably affect nutritional quality, as well as color, and flavor (Yildirim *et al*., 2018). Oxygen scavengers together with active films or modified atmosphere packaging were reported to extend shelf life of strawberries, tomatoes, broccoli, and lettuce by maintaining low oxygen levels and reducing oxidative spoilage (Lee *et al*., 2019; Duong *et al*., 2023). Ethylene absorbers, commonly based on materials such as potassium permanganate ($KMnO_4$) or zeolite, are employed to delay the ripening and senescence of fruits and vegetables by removing ethylene from the surrounding atmosphere (Siracusa *et al*., 2008). Among these, $KMnO_4$ is a widely used ethylene scavenger that oxidizes ethylene into glycol. These agents can be implemented in various forms, including sachets for individual packaging units, coatings for flexible or rigid packaging, impregnated blankets and tubes used during transport, or as nanoparticles exhibiting specific chemical, optical, mechanical, electrical, and magnetic properties (Gaikwad and Lee, 2017).

Antimicrobial active packaging (AAP) systems are designed to inhibit or prevent microbial growth within packaged foods, thereby extending product shelf life and maintaining safety. These systems include edible films and edible coatings in which natural or synthetic antimicrobial agents are incorporated into the packaging matrix to reduce microbial contamination and minimize undesirable quality changes (Sung *et al*., 2013). Edible films and coatings are obtained from biopolymeric matrices based on proteins, lipids, or polysaccharides. While the films are standalone structures with thickness ranging from 0.050 mm to 0.250 mm applied on or in-between food components, coatings are thinner structures, that once applied on foods are part of the final product, without the possibility of being disposed of, separately from the food (Bleoancă and Turtoi, 2017).

Antimicrobial agents can be incorporated, coated, immobilized, or surface-modified onto various packaging materials, depending on their thermal stability, activity and compatibility with the processing method (Divsalar *et al.,* 2018). AAP technologies operate through two primary mechanisms: i) antimicrobial or preservative compounds are gradually released from the packaging material into the food or its headspace, providing continuous protection during storage; or ii) the active agents are firmly bound or immobilized onto the packaging surface, inhibiting microbial growth through direct contact without migration into the product. Commonly used antimicrobial substances include zeolites, niacin, and chitosan, which exhibit broad-spectrum activity against spoilage and pathogenic microorganisms. Zeolites are typically incorporated into polymeric packaging materials through co- extrusion, extrusion, or injection molding (Quintavalla and Vicini, 2002). In most of the applications, the active compounds are gradually released from the film into the package headspace or onto the food surface, creating an antimicrobial environment that inhibits microbial proliferation (Divsalar *et al*., 2018).

In the case of fresh fruits and vegetables, polysaccharide-based materials such as chitosan, alginate, pectin, and starch have been widely used in the development of edible films and coatings to extend shelf life and inhibit microbial growth. Examples of films and coatings containing antimicrobial agents are summarized in Table 1.

Proteins, as edible biopolymers, have attracted considerable attention in food packaging due to their excellent biodegradability, biocompatibility, and film-forming capabilities. Commonly used proteins include gelatin, zein, casein, and soy protein, which functionalised with essential oils, antibacterial agents as chitosan, nisin or metal nanoparticles are efficient against spoilage or pathogenic microflora (Sun *et al*., 2024; Divsalar *et al*., 2018).

These antimicrobial protein-based polymers can be applied directly onto fruits and vegetables as coatings or used as standalone packaging layers, which are able either to release the active agents in a controlled manner or by direct contact release when put in contact with the antimicrobial layer. For example, gelatin-based films functionalised with chitosan and thyme or clove essential oils were able to effectively reduce grape's microbial load (de Souza *et al*., 2018), or zein based films with silver or zinc oxide nanoparticles applied to fresh cut lettuce and broccoli maintained their quality during storage (Dehghani *et al*., 2022). A summary of commonly used antimicrobial agents in protein-based edible films is presented in Table 2.

Table 1. Polysaccharide- based edible films/coatings for fresh produce with antimicrobial agents against pathogens.

Film/coatings	Antimicrobial agents	Tested microorganisms	Fruits tested	Reference
Sodium alginate coatings	eugenol, citral	*Salmonella Typhimurium, Listeria monocytogenes*	sliced apple	Vieira *et al.*, 2019
	sweet orange essential oil	*Listeria* and *Salmonella spp.*	whole tomatoes	Das *et al.*, 2020
	citral nano emulsion	*S. enterica, L. monocytogenes.*	pineapples cubes	Prakash *et al.*, 2020
Egg white protein film	chitosan	*Escherichia coli, Staphylococcus aureus*	whole banana and green grapes	Li *et al.*, 2024
Pectin coatings	extracted pectin	*S. aureus, E. coli*	whole tomatoes	Jhanani *et al.*, 2024
	catechin gallate	*E. coli, S. aureus*	grapes	Huang *et al.*, 2023
Acacia gum coatings	nelumbo nucifera flower extract	*E. coli, S.aureus*	blueberries	Yang *et al.*, 2019
	geraniol	*S. Typhimurium, E. coli*	whole plums	Asgarian *et al.*, 2023
Carboxymethyl cellulose coating	thyme, cardamom and clove essential oils	*S. aureus, E. coli*	whole kiwifruit	Iqbal *et al.*, 2024
Carboxymethyl cellulose film	Fenungreek seed mucilage	*S. aureus, E. coli*	whole apples	Lindi et *al.*, 2024
Starch-aldehyde quercetin microspheres	chitosan	*S. aureus*	whole cherry tomatoes	Sun *et al.*, 2024

By combining the film-forming properties of proteins with the functional activity of bioactive agents, these systems offer a sustainable and powerful active packaging technology for shelf life extension of perishable fruits and vegetables. Sustainability is achieved mainly through the use of biodegradable and renewable materials, but also by replacing the synthetic chemical preservatives and additives used with natural ones, and by minimization of food loss and waste. Overall, protein-, polysaccharide-, and other biopolymer-based edible films or coatings effectively extend the shelf life of fresh fruits and vegetables by delivering antimicrobial and antioxidant agents while maintaining their sensory and nutritional quality during storage (Deshmukh and Gaikwad, 2022).

Table 2. Protein-based edible films with antimicrobial agents.

Film matrix	**Antimicrobial agents**	**Tested microorganisms**	**Reference**
Soy protein concentrate	Free and encapsulated oregano EO*	*E. coli, S. aureus*	dos Santos Paglione *et al.*, 2019
Zein	Nano encapsulated EOs of laurel and rosemary	*L. monocytogenes, S. aureus.*	Goksen *et al.*, 2020
	Chitosan nanoparticles and cinnamon EO	*E. coli, S. aureus*	Vahedikia *et al.*, 2019
Gelatin	Thymol nanoemulsions	*E. coli, B. subtilis*	Li *et al.*, 2020
	Ginkgo biloba extract	*S. aureus, Candida albicans*	Hu *et al.*, 2019
	Bergamot and lemongrass EOs	*L. monocytogenes, S. Typhimurium, E. coli, S. aureus*	Ahmad *et al.*, 2012
	Silver nanoparticle	*S. aureus, E. coli, S. typhimurium, B. cereus, L. monocytogenes,*	Kanmani and Rhim 2014
Fish gelatin	Orange peel pectin	*Enterococcus faecalis, B. cereus, Enterobacter spp.*	Jridi *et al.*, 2020
	Carvacrol	*E. coli, S. aureus*	Neira *et al.*, 2019
	Aqueous extracts from rowanberry, blueberries honeysuckle, and chokeberry pomace	*E. coli, P. fluorescens, S. aureus, L. innocua*	Staroszczyk *et al.*, 2020
	Clove, garlic and origanum EOs	*E. coli, L. innocua, L. monocytogenes, S. Typhimurium*	Teixeira *et al.*, 2014
	Peel powder pomegranate	*E. coli, S. aureus, L. monocytogenes*	Hanani *et al.*, 2019
Whey protein	Lemon and bergamot EO	*E. coli, S. aureus*	Çakmak *et al.*, 2020
	Soy sauce	*E. coli, L. monocytogenes, S. Typhimurium*	García *et al.*, 2020
	Lactobacillus sakei cell-free supernatant	*L. monocytogenes, E. coli*	Beristain-Bauza *et al.*, 2017
	Carvacrol	*L. monocytogenes, S. aureus, S. enteritidis, E. coli*	Wang *et al.*, 2019
Soy protein isolate	Thyme essential oil	*E. coli, S. aureus*	Liu *at al.*, 2023

*EO – essential oil

The incorporation of bacteriophages into edible films represents another antimicrobial strategy, owing to the natural antibacterial activity of bacteriophages and their ability to specifically infect and kill bacteria without impacting the sensory or nutritional quality of foods, in contrast to conventional antimicrobials (Punia et al., 2021; Ramos-Vivas et al., 2021). In addition, phage preparations are already commercially available for use in the food industry as they benefit from GRAS status from Food and Drug Administration (Ly-Chatain, 2014). Phages have also been recognized as a natural antimicrobial agent, offering an innovative solution to replace the commonly used agents in packaging systems. Furthermore, the endolysin enzymes produced by these viral entities also have antimicrobial through enzymatic degradation of the bond between N-acetylmuramic acid and 3D glycan strands in peptidoglycan layer (Narayanan *et al*., 2024). Typically, phage-based films are developed primarily with biopolymers such as proteins, polysaccharides (Lu *et al*., 2021), or as composites (Cui *et al*., 2023). The incorporation of phages into lipid-based matrices for the fabrication of packaging films is still a burden, especially given the inherently poor mechanical properties of this type of film (García-Anaya *et al*., 2023).

Whey protein isolate based coatings incorporating T7 phages have demonstrated variable antibacterial activity against *E. coli* depending on the food substrate: significant reductions of 4 and 2 $\log_{10}$ CFU cm^{-2} were detected in cherries and apple slices respectively, while in cucumbers no reduction was detected, probably due to antiviral compounds presence in the raw material (Vonasek *et al*., 2018); similarly, Amarillas *et al*., (2018) reported a 3 $\log_{10}$ CFU mL^{-1} decrease in *E. coli* when tomatoes were treated with a chitosan- coliphage solution, emphasizing that the antimicrobial effectiveness of phage- based films is strongly influenced by the composition and complexity of the food matrix. Sezer *et al*., (2022) demonstrated that a three- phage cocktail incorporated into coatings made of whey protein concentrate (WPC), chitosan, sodium alginate, and carboxymethyl cellulose reduced *Salmonella enteritidis* and *Salmonella Typhimurium* in strawberries, with the greatest reduction observed for WPC (3.1 $\log_{10}$ CFU g^{-1}), followed by chitosan, sodium alginate, and carboxymethyl cellulose, highlighting that both the type of food and the coating matrix strongly influence the antimicrobial activity of phage-based edible films.

Intelligent packaging

Intelligent packaging is designed to provide real-time information about a product's condition prior to consumption (Wilson *et al*., 2018). These systems incorporate biosensors or chemical sensors that enable continuous monitoring of key quality and safety parameters in fresh fruits and vegetables (Shao *et al*., 2021; Upadhyay *et al*., 2024). Such sensors monitor evolution of parameters like: temperature, freshness, pH levels, the presence of pathogens or toxins, ripeness, carbon dioxide concentration, gas leakage, and various internal or external physiological changes occurring post- harvest. Intelligent packaging technology applied to fruits and vegetables is using labels changing colours dependent on the pH, time- temperature indicators (TTIs), and, in many cases, radio frequency indicators (RFID) systems for temperature monitoring and traceability. These tools provide real-time information on product quality, including visual or digital feedback on freshness, temperature, humidity, and overall storage conditions, supporting both consumers and supply chain managers in maintaining optimal product integrity.

3D printing is an emerging technology that can be used for producing labels monitoring food freshness or pH responsive indicators changing colours employed for fruits and vegetables, able to use a wide range of starches (cassava, potato, and corn), proteins (whey protein and gelatin), and polysaccharides (sodium alginate, agar, and gum arabic) (Chen *et al*., 2022; Tracey *et al*. 2022). These materials not only enable precise printing but also are able to form films or coatings that are safe, biocompatible, and effective, making them ideal for food packaging and label applications (Bao *et al*., 2024). Moreover, 3D printing allows labels to be customized to the specific size, shape, and characteristics of individual fruits or products, combining practicality with high adaptability and functionality (Tang *et al*., 2024). Colorimetric indicators have proven effective in monitoring freshness by detecting spoilage-related compounds such as ethylene, organic acids, and pH-changes (Poyatos-Racionera *et al*., 2018). Freshness indicator labels operate by detecting physiological or environmental changes in fruits. Their mechanisms typically rely on chemical or physical responses to gases (e.g. CO_2, ethylene) or microbial metabolites (e.g., volatile organic compounds- VOCs) released during storage, generating visible signals - such as color changes - that indicate the food product status (Shao *et al*., 2021). pH-responsive color-changing labels offer an additional visual method for monitoring fruit freshness and spoilage by tracking pH variations during storage and transportation (Luo *et al*., 2022). These labels often use pH-sensitive materials, particularly natural pigments like anthocyanins, which display distinct color shifts depending on pH appearing red under acidic conditions and blue or green under alkaline conditions (Huang *et al*., 2025). In addition to freshness monitoring applications, 3D printed structures can be enhanced by antimicrobial compounds to help prolong the shelf life of food products. The antimicrobial can be integrated into 3D-printed films or labels, and the results is a dual-purpose solution: one that not only monitors freshness but also actively suppresses microbial growth (Luo *et al*., 2022).

Gas sensors complement these visual indicators by detecting VOCs emitted during ripening and spoilage, such as ethylene, acetaldehyde, ethanol or ketones, which can be correlated with the physiological state as well as with the duration of the shelf life (Zhag *et al*., 2024). The main type of sensors can be either for oxygen, CO_2 or for ethylene monitoring. Oxygen sensors monitor respiration rates and packaging integrity, carbon dioxide sensors track ripening and senescence through CO_2 accumulation, and ethylene sensors detect ethylene emission to prevent premature ripening or spoilage.

Time temperature indicators (TTIs) are widely used to monitor cumulative temperature exposure over time. By changing color in response to temperature fluctuations, TTIs allow producers, retailers, and consumers to verify whether cold chain conditions have been maintained - a critical factor in MPFV due to increased susceptibility to microbial growth under temperature abuse (Zeng *et al*., 2021).

Advanced biosensor based packaging integrates biochemical sensing elements as enzymes, antibodies, or DNA probes with responsive materials able to detect specific pathogens or toxins. These systems generate visual or digital signals upon contamination and, when coupled with Internet of Things (IoT) platforms, enable continuous remote monitoring and predictive analytics for food safety management (Zhou *et al*., 2019).

Radio-frequency identification (RFID) systems further enhance intelligent packaging by allowing non- contact tracking, real time data logging, and integration into digital traceability platforms (Ruiz-Garcia and Lunadei, 2011).

The main challenges of active and intelligent packaging adoption on large scale despite the technological advances are represented by increased costs for their implementation, missing regulatory steps for sensors, as well as the standardized performance validation limits for widespread use. Consumer acceptance is also critical, as unfamiliar technologies may raise concerns about chemical migration, over- packaging, or data privacy. Nonetheless, the combination of visual indicators, gas sensors, TTIs, and biosensor- based systems represents a powerful strategy for monitoring fruit quality and extending shelf life throughout storage and transport.

Artificial Intelligence applications in MPFV processing and monitoring

The complexity and variability inherent in MPFV production makes it a suitable field for the implementation of Artificial Intelligence (AI) technologies. AI enables advanced data analysis, pattern recognition, and predictive modelling, which can improve process control, optimize quality management, and enhance traceability across the supply chain. By integrating AI with sensors, computer vision, and IoT platforms, the food industry can shift from traditional quality control methods to data-driven, real-time decision-making systems (Misra *et al.*, 2022).

AI-based image analysis and computer vision technologies are increasingly applied in the inspection and grading of fruits and vegetables. High-resolution cameras and hyperspectral imaging systems can detect surface defects, bruising, discoloration, or microbial spoilage that are not visible to the human eye (Kamilaris *et al.,* 2020). Machine learning algorithms - especially convolutional neural networks (CNNs) - can automatically classify products according to quality parameters such as ripeness, size, and color, with high accuracy (Jha *et al*., 2023).

These systems not only standardize quality assessment but also reduce human subjectivity and labor costs. In MPFV processing lines, AI-enabled cameras can monitor the cutting, peeling, and sorting stages, ensuring uniformity and early detection of defective or contaminated batches.

Shelf life is a critical aspect of MPFV safety and commercial viability. Conventional methods for estimating shelf life rely on empirical data and periodic microbial testing, which can be time-consuming and limited in predictive power. AI models, particularly artificial neural networks (ANNs) and support vector machines (SVMs)**,** can analyze multidimensional datasets including temperature history, humidity, gas composition, and microbial counts to predict spoilage kinetics and remaining shelf life with high precision (Wang *et al*., 2021).

Such predictive analytics support better inventory management, reduce food waste, and optimize logistics. According to da Costa *et al.,* (2021), when integrated with TTIs and intelligent packaging sensors, AI algorithms can dynamically update shelf life predictions based on real time environmental data.

AI applications in microbial risk assessment are expanding rapidly. Machine learning algorithms can analyze large microbiological datasets to identify patterns and correlations between environmental conditions, contamination and health risks (Zhao *et al*., 2022). For instance, AI models can predict the likelihood and risk exposure of *Listeria monocytogenes* contamination in processing facilities by analyzing temperature, humidity, and sanitation data collected from sensors.

Deep learning algorithms can also enhance the sensitivity of biosensors used in smart packaging by improving signal recognition and noise reduction. Combined with computer vision, AI can enable automated detection of anomalies in color-changing indicators, facilitating real- time contamination alerts.

Traceability remains a cornerstone of the modern food safety management. AI enhances traceability by enabling rapid data processing, anomaly detection, and predictive analytics across complex MPFV supply chains. When combined with blockchain technology, AI can create tamper proof digital records of each production stage from farm to retail, ensuring transparency and accountability (Galvez *et al*., 2018).

This integration supports faster recall procedures, more accurate source attribution during outbreaks, and facilitates the increase in consumer trust. Moreover, AI-driven blockchain systems can optimize data flow by filtering redundant information and ensuring data consistency, thereby reducing the computational load associated with blockchain networks (Rejeb *et al*., 2022).

AI-based decision support systems (DSS) provide predictive insights that assist producers and quality managers in optimizing process parameters, sanitation schedules, and resource allocation. For instance, predictive maintenance models can forecast equipment failures or hygiene risks before they occur, minimizing downtime and contamination probability (Misra *et al*., 2022). Reinforcement learning algorithms can also be employed to dynamically adjust process variables such as airflow, humidity, or cutting speed to achieve optimal product quality and safety outcomes. Despite its promising potential, the application of AI in MPFV processing faces several challenges. These include limited availability of high-quality datasets, the need for data standardization, integration costs, and concerns about data privacy. Moreover, AI algorithms require continuous validation under real production conditions to ensure reliability and accuracy.

The integration of active and intelligent packaging technologies within a robust cold chain infrastructure enhances their effectiveness. Packaging sensors that detect deviations in temperature, humidity, or gas composition can trigger corrective actions or alerts in real time, reducing waste and improving safety assurance.

Combined with AI-driven data analytics, these technologies enable predictive modeling of product quality and shelf life, marking a paradigm shift from reactive to proactive food safety management (da Costa *et al*., 2021).

Consumer Practices and Communication Strategies

Consumer behavior is a critical determinant of food safety outcomes for MPFV. Even when production and supply chains comply with strict regulatory standards, improper handling, storage, or preparation at the household level remains a significant source of foodborne risks (Redmond and Griffith, 2003). Evidence suggests persistent gaps between recommended practices and actual consumer behavior, underscoring the need for targeted education and communication strategies.

Recent surveys in European populations highlight the widespread occurrence of risky behaviors. Kasza *et al*., (2022) reported that, across ten countries, 26% of consumers do not rinse vegetables or fruits before consumption, 17% reuse knives without cleaning after cutting raw poultry, and 21% reuse chopping boards under similar conditions. Moreover, 73% fail to wash chopping boards with soap before reuse, 89% neglect to verify eggs for *Salmonella*-free health marks, and 80% do not follow on-pack cooking instructions for frozen or pre-prepared foods. Dumitrașcu *et al*., (2020) found that 21% of consumers are unaware of their refrigerator temperature, with 80% of households exceeding the recommended 4°C. Additionally, qualitative studies indicate that handwashing after handling raw poultry is inconsistently practiced (Didier *et al.*, 2021) favoring cross-contamination. These findings demonstrate that consumer practices can directly influence the microbial safety of MPFV, highlighting the importance of education and clear communication strategies.

Labels serve as a primary interface between producers and consumers, providing information on shelf life, storage conditions, allergens, and safe handling instructions. Research shows that labels employing clear language, visual cues, and concise instructions improve compliance and reduce microbial risks associated with improper handling (Frewer *et al*., 2016). Visual icons, color coded indicators, and QR codes linking to detailed tutorials are increasingly employed to enhance users` comprehension.

Government agencies, industry actors, and non-governmental organizations have implemented awareness campaigns targeting safe food handling. These campaigns use diverse communication channels, including mass media, point of sale materials, and digital platforms. They are essential for vulnerable populations such as children, the elderly, and immunocompromised individuals (Frewer *et al*., 2016).

Digital technologies offer interactive opportunities to enhance consumer education. Serious games, mobile applications, and QR-linked tutorials can engage consumers while providing tailored guidance on handling, storage, and shelf life management (Ueland, 2019; Koch *et al*., 2022). Social media provides a platform for targeted messaging to young consumers additional to traditional ones (Borda *et al*., 2021; Tiozzo *et al*., 2018). Behavioral insights, including nudges, gamification, and visual cues, have been shown to bridge the gap between knowledge and actual practices, encouraging safe handling behaviors in home environments.

Effective risk communication should prioritize accuracy, clarity, timeliness, and practicality. Educational strategies that integrate both traditional and digital tools are more likely to influence behavior positively. For MPFV, combining labeling, interactive digital tools, and awareness campaigns creates a multi layered approach to reduce foodborne illnesses determined by perishable food products consumption.

Conclusions

In the last decade consumer's preferences for MPFV increased due to their fresh-like sensorial characteristics which are usually associated with their health benefits, as well as convenience in use. However, their nutrient richness and high-water activity content together with the lack of processing step for microbial inactivation determines MPFV to be part highly susceptible to microbial contamination and further growth.

This review highlights the complex interplay of pre-harvest, postharvest, and consumer related factors that influence MPFV safety and quality. Moreover, innovative packaging, as active and intelligent solutions coupled with AI technology allows predictive modeling of shelf life, rapid detection of anomalies, and optimized decision making across the supply chain. Such technologies, when combined with robust cold chain management, can significantly enhance safety, reduce waste, and improve overall supply chain efficiency.

Despite these advances, challenges remain. High costs, regulatory uncertainties, standardization gaps, and consumer acceptance are key barriers to widespread adoption. Data driven AI systems require reliable datasets, validation under real-world conditions, accurate and transparent interpretability. Consumer education is equally critical, as improper handling, storage, or preparation at the household level can compromise even the most technologically advanced safety measures.

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