



Innovative Technologies in Shelf Life Extension: Recent Developments in The Food Industry

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HIGHLIGHTS

- Innovative technologies enhance shelf life, quality, and food sustainability.
- Smart packaging ensures food safety by monitoring freshness and reducing waste.
- Nanotechnology offers advanced solutions for food safety and shelf-life extension.
- Biopreservation uses natural antimicrobials to improve safety and reduce spoilage.

Abstract

This research explores innovative food preservation technologies designed to extend product shelf life and tackle with challenges like microbial contamination, oxidation, and physical degradation. It examines the biological, chemical, and physical factors that drive spoilage and evaluates emerging solutions such as smart packaging, advanced biopreservation methods, and nanotechnology. By analyzing these technologies' theoretical foundations and practical applications, the study highlights their impact on food quality, safety, and sustainability. It also assesses the scalability of these innovations and their potential to transform industrial practices. Ultimately, the research provides a strategic framework for advancing sustainable food preservation methods, aligning technological advancements with the food industry's environmental and economic challenges, and contributing to global efforts in food security and waste reduction.

Keywords: Shelf Life; Innovative Technologies; Food Industry; Consumer Health; Food Safety.

1. Introduction

In the dynamic landscape of the food industry, the pursuit of innovative technologies to extend the shelf life of food products has emerged as a key area of research and development. Recent breakthroughs in food science have led to the introduction of innovative approaches designed to maintain the freshness and quality of perishable items. From the implementation of processing and packaging barriers to the incorporation of nanosystems into edible coatings, the sector has witnessed a paradigm shift toward more effective and sustainable preservation techniques. The shelf life refers to the duration during which food products remain safe for consumption and retain their desired quality, playing a crucial role in ensuring food safety and

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maximizing economic efficiency (Man, 2015). Food spoilage, resulting from factors such as microbial proliferation, oxidation, and physical damage, contributes to substantial economic losses and presents significant risks to consumer health. As a result, the extension of shelf life has emerged as a critical focus within research and development in the food industry (Rawat, 2015).

In the food industry, the primary motivation behind the ongoing research and development of innovative technologies and strategies is the effort to extend the shelf life of food products (Kandirmaz, 2020). A variety of biological, chemical, and physical factors are integral to the effective long-term preservation and quality maintenance of food products (Santana et al. 2020). Biological influences, particularly microbial and enzymatic activity, are primary contributors to the acceleration of food spoilage, while chemical processes such as oxidation, souring, and rancidification undermine the structural integrity and safety of food products (Mol et al. 2007). Additionally, physical factors, including humidity levels, light exposure, and temperature variations, may have a direct effect on the shelf life of food materials (Birania et al. 2022).

To overcome these challenges and optimize food preservation, the food industry has made substantial progress in the development of groundbreaking technologies and methodologies (Doğan & Aydın, 2020). Unconventional progress has been achieved in the monitoring and preservation of food freshness through the implementation of smart packaging technologies, which incorporate sensors, indicators, and active packaging components (Deshwal & Panjagari, 2022). Furthermore, sophisticated biopreservation methods, incorporating natural antimicrobials, antioxidants, and biofilm applications, present environmentally sustainable alternatives to traditional preservatives, thereby considerably extending the shelf life of food products (Kuswandi et al. 2022). Physical and biophysical processes, including high-pressure treatments, cold plasma therapies, electroporation, and radiation techniques, have demonstrated their efficacy as sterilization and preservation methods (Kaur, 2024). Additionally, the advent of nanotechnology has introduced novel approaches in food safety, employing nanoparticles, nanocoatings, and nanosensors to improve antimicrobial and antioxidant characteristics (Anvar et al. 2021). These novel applications further elevate food safety standards through precise monitoring and robust protection mechanisms against contaminants (Ungureanu et al. 2022).

Moreover, the adoption of innovative technologies like RFID tags, QR codes, biosensors, and advanced tracking systems has significantly improved transparency and quality control throughout the supply chain, especially in food traceability and freshness monitoring (Lau et al. 2022). From an environmental sustainability standpoint, the adoption of eco-friendly packaging solutions and the evaluation of energy consumption are key factors in devising strategies aimed at reducing the environmental impact of food industry operations (Gustafson et al. 2022). Within this framework, it is crucial to assess the environmental implications of preservation techniques and packaging materials to encourage more environmentally-conscious practices and minimize waste in the food industry. These strategies represent important strides in improving the sustainability of food production systems and minimizing their ecological footprint. In addition, the integration of innovative technologies and packaging solutions offers considerable potential to reduce food waste while further enhancing resource efficiency. Therefore, such efforts are vital in advancing the food industry's role in achieving global food security and sustainability objectives (Poyatos-Racionero et al. 2018).

2. Factors Influencing Shelf Life

The shelf life of food denotes the duration during which a product retains its quality, safety, and nutritional integrity under defined storage conditions before it is considered unsuitable for consumption (Steele, 2004). It is a fundamental component of food preservation and quality control, with direct implications for consumer acceptability and safety (Hosseini & Jafari, 2020). A multitude of factors, including packaging, storage environments, formulation, and processing methodologies, influence the shelf life of food products (Marrez et al. 2022). In this context, shelf life transcends the simple physical or chemical degradation of the food product, incorporating the consumer's interaction with the product, thereby positioning it as a composite function (Rasane et al. 2014).

Food products originate from biologically active raw materials that are naturally susceptible to degradation over time. This degradation process can result in food safety concerns and a decline in consumer acceptability. Degradation is generally categorized into three primary types: biological, chemical, and physical. These forms of degradation often interact, with one type potentially inducing another (Ozyilmaz et al. 2020).

Microorganisms and enzymatic activities are central biological factors influencing the shelf life of food products. In this regard, enzymes produced by psychrotrophic microorganisms can significantly shorten the shelf life of products like cheese by causing undesirable flavor changes, extended coagulation times, and higher concentrations of free fatty acids and amino acids (Santana et al. 2020). Psychrophilic bacteria, with a more profound effect on food quality and safety compared to mesophilic counterparts, highlight the need for focused research on these microorganisms in relation to shelf life (Mol et al. 2007). On the other hand, bacteriocins produced by specific bacteria, such as *Lactobacillus plantarum*, have been shown to impact the shelf life of refrigerated meat products (Fiorentini et al. 2001). Therefore, a comprehensive understanding of microbial composition and activity is essential for the precise determination of food shelf life (Mercan & Sert, 2021).

The dominant microorganisms and their amount/load at the end of shelf life may vary depending on storage conditions, indicating the necessity of careful monitoring of microbial growth to ensure quality and safety (Parlapani et al. 2014). The application of innovative active packaging systems, including those utilizing plant extracts like chitosan, may enhance shelf life by regulating spoilage and functional microorganisms in products such as Mozzarella cheese (Conte et al. 2007). The combination of chitosan with bacteriocins, such as plantaricin EmF, has proven effective in inhibiting pathogens like *Listeria monocytogenes*, disrupting cell membranes, leading to cell death and consequently extending the shelf life of meat products (Zhao et al. 2022). Moreover, in the case of dairy products, the presence of thermotolerant bacteria, which are resistant to thermal processing, is a critical factor in spoilage and must be considered in shelf life studies (Júnior et al. 2018).

Chemical factors, including oxidation and rancidity, play a crucial role in determining the shelf life of food products. Oxidative rancidity, a prevalent chemical reaction in both solid and liquid fats, degrades food quality by altering its color, odor, and flavor, which ultimately leads to a reduction in product shelf life (Othón-Díaz et al. 2023). Foods rich in unsaturated fats, with oxidative or hydrolytic enzymes, are particularly vulnerable to rancidity (Meriles et al. 2019). Additional factors, such as elevated pH, polyunsaturated fatty acids, and non-protein nitrogen compounds, further heighten this vulnerability, promoting accelerated microbial growth, oxidation, and autolytic reactions, all of which contribute to a shortened shelf life (Zolfaghari et al. 2023).

Studies on food preservation methods have increasingly concentrated on the application of antioxidants to counteract oxidative degradation and significantly prolong shelf life. In this context, natural antioxidants derived from oak species, such as *Quercus* sp., have shown promise in reducing oxidative deterioration in food products, thereby improving their stability and extending their shelf life (Othón-Díaz et al. 2023). In a similar vein, the incorporation of plant extracts and essential oils into edible films has proven effective in preventing lipid oxidation and microbial spoilage, especially in prolonging the shelf life of aquatic products like common carp fillets (Zolfaghari et al. 2023).

In low-moisture bakery products, on the other hand, the oxidation level of added fats is a key factor influencing product stability and shelf life. Modeling the oxidation state of fats has been employed to develop predictive models, using measures like peroxide value to estimate shelf life, thereby providing valuable information on the role of chemical factors in product stability (Manzocco et al. 2020). In particular, the kinetic modeling of lipid oxidation reactions has become an integral method for predicting shelf life and gaining insight into the impact of chemical alterations on product degradation over time (Jaimez-Ordaz et al. 2019).

Physical factors such as humidity, light, and temperature are crucial determinants of the shelf life of food products. Among these, the relative humidity within packaging systems plays a critical role in preserving product quality and extending shelf life in terms of sorption isotherm. For example, packaging systems that maintain required relative humidity have been demonstrated to significantly extend the shelf life of regional cheese varieties (Pantaleão et al. 2007). Additionally, the interaction between environmental humidity and

food formulations can affect chemical stability, potentially reducing shelf life due to issues such as excessive browning (Ortiz et al. 2008).

Temperature control is equally vital for preserving food quality and prolonging shelf life. Optimal storage temperatures minimize the negative effects of a cutting process and slow respiration rates in freshly cut produce, thereby enhancing their shelf life (Kaur et al. 2011). On the other hand, elevated storage temperatures and high humidity levels can severely reduce the shelf life of food products, highlighting the need for appropriate environmental conditions during storage and transportation (Wolbert et al. 2022).

Research has also underscored the impact of storage temperature on the shelf life and quality attributes of fruit products, particularly tropical fruits like pineapple, where temperature fluctuations have been shown to directly and significantly affect both the quality and longevity of the fruit products (Gomez et al. 2023). The influence of humidity levels on food quality and shelf life has been well-documented in the literature. For instance, elevated storage humidity has been found to negatively impact fruit quality characteristics and increase the incidence of fruit cracking, especially in apples. These findings highlight the critical role of humidity regulation in maintaining fruit quality during storage (Lee et al. 2019). Furthermore, the absorption of water in food products has been observed to substantially affect the shelf life, particularly of emerging snack foods. Previous research underscores the importance of accounting for humidity effects when developing food preservation strategies (Pérez-Flores et al. 2015).

As discussed previously, each factor directly influences the rate of food degradation, thereby negatively affecting shelf life. In this regard, the precise identification and measurement of food spoilage are essential for providing safe and high-quality food products to consumers. For food manufacturers, accurately determining shelf life and adopting innovative technologies to minimize spoilage have become crucial for maintaining both safety and flavor.

3. Innovative Technologies for Shelf Life Extension

Food loss and waste represent significant challenges with severe consequences for global agricultural sustainability and environmental balance. Around one-third of global food production is lost due to spoilage or disposal, highlighting the urgent need to address this issue from both food security and environmental sustainability perspectives (Cattaneo, Federighi, & Vaz, 2021). Major contributors to food loss and waste include post-harvest management, processing, packaging, distribution, and consumption, which collectively account for a substantial portion of these losses. This not only compromises food quality but also increases risks related to food safety and security. However, innovative technologies designed to extend food shelf life present considerable potential in addressing these issues (De Corato, 2020).

In recent years, the growing demand for fresh produce and changing consumption patterns have heightened the importance of ensuring food safety and quality. In this regard, innovative technologies aimed at prolonging shelf life have become essential in the food industry (Mostafidi et al. 2020). The following section discusses advanced bioprotection techniques, such as smart packaging technologies, natural antimicrobials, antioxidants, and biofilm applications, alongside physical and biophysical treatments like high-pressure processing, cold plasma treatment, electroporation, and irradiation, all of which are crucial in maintaining food freshness and extending shelf life.

4. Smart Packaging Technologies

Smart packaging systems provide efficient solutions for addressing challenges related to the transportation and storage of perishable food items, significantly extending their shelf life (Alam et al. 2021). Smart packaging technologies provide innovative solutions for the food industry, aimed at extending the shelf life of products. (Jafarzadeh et al. 2021). Among these innovative methods, active packaging stands out as a subset of smart packaging, aiming to optimize product preservation by actively modifying the internal atmosphere of the package (Clodoveo et al. 2021). In contrast to conventional passive packaging methods, active packaging systems directly interact with the food product, offering substantial benefits such as extended shelf life and

enhanced product quality (Kujundziski & Chamovska, 2020). These advancements are designed to address the increasing consumer demand for safe and long-lasting food products (Deshwal & Panjagari, 2022). The incorporation of smart sensors into food packaging has emerged as a key component for both effectively monitoring and ensuring food quality and safety. These sensors are capable of detecting, tracking, and verifying the condition of food products, thereby facilitating improved preservation and prolonged shelf life (Kuswandi et al. 2022).

Smart packaging employs various indicators that are essential for preserving and monitoring the quality of food products. These indicators, either inside or outside the packaging, offer crucial insights into food quality by monitoring external environmental conditions and headspace gases (Türker, 2023). They are especially designed for parameters such as temperature, microbial spoilage, packaging integrity, physical impact, and authenticity throughout the storage period of the food. Some indicators function by directly interacting with the food through chemical reactions, while others relay information about the food's status without such interactions. These indicators are vital for ensuring food safety and consumer health, and their development continues in parallel with advancements in packaging technologies. A variety of these indicators, along with their principles and application areas, are summarized in Table 1. (Türker, 2023).

Table 1. Examples of Indicators Used in Smart Packaging (Türker, 2023)

Type	Principle/Marker	Information Provided	Application Area
Time-Temperature Indicators (external)	Mechanical, chemical, enzymatic	Storage and transport conditions	Preservation of chilled or frozen foods
O ₂ indicators (internal)	Redox dyes, pH dyes, enzymes	Storage conditions and packaging leakage	Foods packaged in reduced oxygen environments
CO ₂ indicators (internal)	Chemical	Storage conditions and packaging leakage	Modified or controlled atmosphere packaging
Microbial growth and freshness indicators	pH dyes, specific metabolite-reactive dyes	Microbial quality of food (e.g., spoilage)	Quality control of perishable foods like meat, fish or poultry
Pathogen indicators (internal)	Toxin-reactive chemicals and immunochemicals	Detection of specific pathogenic bacteria (e.g., <i>E. coli</i> O:157)	Quality control of perishable foods like meat, fish or poultry

These innovative packaging technologies incorporate a variety of methods, including time-temperature indicators, gas sensors to monitor carbon dioxide and oxygen levels, and sensors capable of detecting food spoilage and ripeness (Halonen et al. 2020). Additionally, technologies like RFID tags for product tracking and verification enhance food safety and quality, offering significant potential for extending shelf life (Halonen et al. 2020). Smart packaging systems with antimicrobial properties are also noteworthy for their ability to prolong food product shelf life (Tongnuanchan & Benjakul, 2014). The shift from passive to smart packaging systems in the food industry has been primarily driven by the demand for improved food quality, safety, and shelf life. The incorporation of smart sensors and advanced packaging designs into active packaging technologies is paving the way for more efficient, dependable, and sustainable solutions, providing considerable benefits for both manufacturers and consumers (Drago et al. 2020).

5. Advanced Biopreservation Methods

The increasing importance of advanced biopreservation techniques in enhancing food storage methods is becoming more apparent. These techniques involve the use of natural preservatives, such as antimicrobial polyphenols derived from plants, which have shown significant potential in improving both food safety and quality (Chibane et al. 2018). Additionally, there is growing interest in the food industry in utilizing natural plant-based antioxidants, which offer benefits like extended shelf life and enhanced product quality (Lourenço et al. 2019). The use of natural antioxidants for food preservation, particularly when combined with other components in a synergistic manner, is widely acknowledged for its positive impact on food products (Lourenço et al. 2019).

Additionally, the integration of bioprotective cultures into food preservation practices has become a widely adopted strategy to maintain product quality throughout its shelf life (Nielsen et al. 2021). These cultures possess antimicrobial properties that contribute to preserving food quality and preventing spoilage during storage (Marzano et al. 2022). The incorporation of natural antioxidants and antimicrobials into food packaging materials marks a significant advancement in enhancing food safety and quality (Baghi et al. 2022). The combination of edible biopolymers with natural antimicrobials ensures the production of safer, higher-quality food products (Baghi et al. 2022). Moreover, the protective effects of natural protein-derived antioxidant peptides, particularly on meat and dairy products, are under investigation as a promising approach for preserving such foods (Zhu et al. 2022). The increasing use of natural additives and biopreservatives in the food industry reflects the growing consumer demand for clean-label products. Similarly, the adoption of natural preservatives such as nisin, a bioactive peptide, for biopreservation in food has become more prevalent as part of this trend (Amiri et al. 2021). This shift towards replacing synthetic antioxidants with natural alternatives aligns with the objective of enhancing both food quality and consumer health (Uzombah, 2022).

6. Physical and Biophysical Processes

Innovative technologies, including high-pressure processing, cold plasma treatment, electroporation, and irradiation, have emerged as promising strategies for extending the shelf life of food products. These physical and biophysical methods provide distinct advantages in food preservation. Among these, cold plasma technology, recognized for its non-thermal characteristics, has gained considerable interest in the food industry due to its ability to inactivate microorganisms and enhance food safety without compromising sensory and nutritional qualities (Birania et al. 2022). Studies have revealed that cold plasma treatments exert minimal effects on the chemical, physical, sensory, and nutritional properties of diverse food products, establishing it as a highly promising technology for prolonging shelf life (Birania et al. 2022). Similarly, high-pressure processing, such as high hydrostatic pressure processing, is widely regarded for its effectiveness in extending shelf life and preserving nutrients in food products (Kaur, 2024). As a non-thermal method, these techniques ensure the maintenance of food quality and safety while significantly prolonging shelf life (Kaur, 2024).

Electroporation technology, which utilizes electric fields to generate pores in cell membranes, allows for enhanced antibacterial activity and bacterial inactivation, even at low voltage levels (Wang et al. 2018). This method effectively controls microbial contamination by inducing oxidative stress and modifying cell membrane permeability, making it a valuable tool in food preservation. Likewise, irradiation techniques, such as those involving UV-C spectral emissions, have been investigated for their effects on the textural and color characteristics of food products. These methods serve as powerful sterilization tools that preserve food quality and safety during storage (Vukić et al. 2016).

Therefore, the incorporation of physical and biophysical techniques to extend the shelf life of food products is considered a major breakthrough in food preservation. These innovative technologies are pivotal in ensuring food safety, quality, and preservation, addressing the growing demand for fresh, high-quality food among consumers (Speranza et al. 2021). Additionally, they are recognized for providing effective solutions

to microbial spoilage and contamination challenges within the food industry, all while safeguarding the nutritional and sensory attributes of the food. Beyond enhancing shelf life, these technologies also play a role in mitigating food waste and achieving sustainability objectives throughout the food supply chain. As a result, food industry researchers and producers are consistently motivated to explore the full potential of these innovative methods and to develop novel strategies and applications aimed at improving food safety and quality (Kaur, 2024).

7. Nanotechnology and Its Applications in Food Safety

The integration of nanotechnology into food safety and preservation is revolutionizing the food industry with innovative solutions. One notable advancement is nano-packaging, which incorporates nanotechnology into food packaging, offering significant potential to enhance food safety by adding antimicrobial properties into packaging materials to combat foodborne pathogens (Anvar et al. 2021). These innovations in packaging materials are playing a crucial role in transforming food preservation techniques, representing a groundbreaking approach to ensuring the safety and quality of food products (Bajpai et al. 2018). Moreover, the application of engineered nanomaterials, particularly nanosensors that directly impact food safety and consumer health, is creating new opportunities for progress within the industry (Martirosyan & Schneider, 2014).

The use of engineered nanomaterials in food, particularly nanosensors that can directly influence food safety and consumer health, is revolutionizing the sector (Martirosyan and Schneider, 2014). Certain nanoparticles, including metallic and metal oxide variants, offer promising opportunities for real-time monitoring of food product quality and safety during the production process, thereby contributing to the advancement of food safety standards (Ungureanu et al. 2022). The use of metal nanoparticles within the agri-food sector further emphasizes the versatility and potential of nanotechnology in improving both food safety and quality (Rastogi et al. 2021). The incorporation of nanotechnology, particularly nano-packaging and nanosensors, into food safety applications, along with advancements in ensuring the safety and security of food products, enhances the industry's ability to meet the increasing and evolving demands of consumers, while holding substantial promise for the future of the food sector. These innovations facilitate significant progress in delivering safer, higher-quality, and longer-lasting products to consumers, thereby contributing to the reduction of food waste and supporting the progress toward sustainable food systems (Ahmed et al. 2022).

8. Innovative Solutions in Food Traceability and Freshness Monitoring

Significant progress has been made in the fields of food traceability and freshness monitoring through the adoption of technologies such as RFID tags, QR codes, and biosensors. RFID systems, in particular, offer distinct advantages over traditional barcode systems in terms of food traceability (Abad et al. 2009). These systems facilitate automatic data collection throughout the supply chain, leading to substantial enhancements in visibility and traceability (Zhu, 2017). Moreover, RFID technology has found widespread application in various sectors of the food industry, including supply chain management, temperature monitoring, and food safety assurance (Kumar et al. 2009). The integration of blockchain technology has further improved traceability by offering a decentralized system that supports the tracking of food products along the supply chain (Wang et al. 2022). This approach enhances transparency and security in the traceability process. In addition, the implementation of QR codes has emerged as an innovative solution to improve food traceability, minimize food waste, and provide consumers with precise information about product quality and pricing (Žurbi, 2023).

Consumers have shown favorable attitudes towards using QR codes as a means to discover food traceability systems (Lau et al. 2022). RFID technology plays a pivotal role in enabling real-time traceability and monitoring of cold chains, thereby enhancing food safety and quality (Liang et al. 2015). The integration of blockchain with RFID technologies has facilitated the creation of food traceability systems that combat fraud and improve supply chain transparency (Deng & Feng, 2020). Furthermore, RFID technology has been applied

to develop traceability systems specifically for certain food products, ensuring their authenticity and maintaining quality standards (Zhang et al. 2019). In summary, the fusion of RFID tags, QR codes, biosensors, and blockchain technology has transformed food traceability and freshness monitoring systems, offering effective and reliable tracking of food products from production through to consumption while ensuring safety, quality, and transparency across the entire supply chain (Ahmed et al. 2022).

9. Innovative Technologies from a Sustainability Perspective

The potential of innovative technologies to support both shelf-life extension and sustainability objectives within the food industry is crucial in reshaping the sector. Active packaging, a novel strategy that incorporates active elements into packaging materials to preserve or enhance product quality, has gained considerable attention in the field (Drago et al. 2020). These methods facilitate real-time monitoring of packaging processes, thereby prolonging shelf life and improving the safety and quality standards of food products (Neethirajan et al. 2018). The incorporation of natural active agents into sustainable packaging materials marks a significant advancement, regarded as a revolutionary development in the realm of active packaging aimed at extending shelf life and improving food safety (Realini & Marcos, 2014).

The application of biodegradable polymer films or coatings, reinforced with either natural or synthetic fillers, has shown considerable promise in enhancing the physicochemical, mechanical, antimicrobial, and antioxidant characteristics of packaging materials, thereby contributing to shelf-life extension (Gagaoua et al. 2021). Additionally, significant research has focused on the integration of antimicrobial nanoparticles and biodegradable polymer composites into active packaging systems, aiming to maintain the high quality of food products over prolonged periods (Omerović et al. 2021). Among the innovative approaches, edible packaging, which merges food with packaging through advanced material design, is emerging as a promising sustainable solution (Zhao et al. 2021). Biopolymer composite nanofibers, produced through electrospinning, have proven effective in sustainably packaging fruits and meats, demonstrating antibacterial properties and enhancing freshness preservation (Líu et al. 2020). Overall, the implementation of innovative technologies such as active packaging, biodegradable materials, and edible packaging provides a sustainable approach to extending the shelf life of food products. These developments not only play a significant role in minimizing food waste but also improve food safety and quality throughout the supply chain (Rangaraj et al. 2021).

10. Challenges and Limitations in Practical Applications

One of the main factors limiting the widespread use of new technologies that extend the shelf life of processed and fresh food products is the possibility that these technologies may misinform the consumer about the inherent freshness and spoilage of the product. Therefore, each new technology needs to be demonstrated to be 100% reliable through detailed testing before it can be implemented. However, the wide variety of food products and some differences depending on the raw materials used make this process difficult (Hassoun et al, 2023). Moreover, the insufficient consumer awareness regarding the use of these novel technologies in the food sector may pose a significant barrier to their widespread adoption (Giacalone & Jaeger, 2023). To facilitate the broader implementation of these technologies in food applications, they must be acceptable, safe, and cost-effective for both the industry and consumers.

11. Conclusions

Biological factors (such as microorganisms and enzymatic activities), chemical factors (such as oxidation and rancidity), and physical factors (such as moisture, light, and temperature) exert substantial influence on the shelf life, quality, and safety of food products (Pandian et al. 2021). The development of innovative technologies designed to control these factors plays an essential role in mitigating food spoilage and prolonging shelf life. Smart packaging technologies, which incorporate modified atmosphere and active packaging features, help maintain food freshness, thereby providing consumers with safer products (Sonwani et al. 2022). Biopreservation techniques, including the use of natural antimicrobials, antioxidants, and biofilm applications, are highly effective in preventing microbial spoilage and extending shelf life (Zhang et al. 2021).

Furthermore, physical and biophysical processes contribute to food safety by inactivating pathogenic microorganisms, utilizing techniques such as high-pressure processing, cold plasma, and irradiation (Sonwani et al. 2022).

Nanotechnology-based solutions, such as nanoparticles, nano-packaging, and nanosensors, slow down food spoilage and prolong shelf life through interactions at the microscopic level (Ghosh et al. 2022). Traceability technologies, including RFID tags, QR codes, and biosensors, enable real-time monitoring of fresh produce, offering consumers valuable insights into product freshness and safety (Saqqa, 2020). Environmentally sustainable packaging solutions and energy-efficient innovations not only reduce food waste but also promote environmental sustainability (Ghosh et al. 2022). Cross-disciplinary collaboration between food science, biotechnology, nanotechnology, and materials science accelerates the integration of these innovative solutions into broader applications. The incorporation of these technologies in the food industry enhances consumer health and food safety while simultaneously laying the foundation for building a sustainable food system. In conclusion, the widespread adoption of these innovative technologies empowers the food industry to produce safer, longer-lasting, and more environmentally friendly products, advancing the achievement of global sustainability goals for the industry.

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