International Journal of Zoology and Applied Biosciences ISSN: 2455-9571
Volume 10, Issue 6, pp: 271-274, 2025 (Special Issue)
https://doi.org/10.55126/ijzab.2025.v10.i06.SP059 http://www.ijzab.com

Review Article

EMERGING FOOD PROCESSING TECHNIQUES FOR ENHANCING SHELF LIFE AND PREVENTING SPOILAGE

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Article History: Received 19th September 2025; Accepted 28th October 2025; Published 25th November 2025

ABSTRACT

Food spoilage remains a major global challenge affecting food safety, economic sustainability, and consumer health. Advances in food processing technologies have enabled more efficient strategies for extending shelf life while preserving nutritional and sensory quality. This review examines emerging techniques such as high-pressure processing (HPP), pulsed electric fields (PEF), cold plasma treatment, ohmic heating, ultraviolet (UV-C) irradiation, and nanotechnology-enabled packaging. These technologies minimize microbial growth, enzymatic degradation, and oxidative reactions responsible for spoilage. Comparative evaluation demonstrates that non-thermal methods maintain product freshness more effectively than traditional thermal processing. The review highlights technological potential, limitations, industrial feasibility, and future research needs for widespread adoption.

Keywords: Metal nanoparticles, Metal oxide nanoparticles, Physicochemical properties, Structural analysis.

INTRODUCTION

Food spoilage is a major concern for global food industries due to its impact on safety, nutritional value, and economic losses. Spoilage results from microbial contamination, enzymatic activity, oxidation, and physical or chemical changes during storage. Traditional techniques such as pasteurization, dehydration, salting, and thermal processing offer some level of preservation but often compromise sensory and nutritional quality. Emerging food processing techniques—particularly non-thermal technologies are gaining attention due to their ability to inactivate microorganisms while retaining nutritional and sensory attributes. Technologies such as high-pressure processing (HPP), pulsed electric fields (PEF), cold plasma, ultraviolet (UV-C) treatment, and nanotechnology-based packaging offer promising solutions for the food industry. This paper reviews the principles, applications, and effectiveness of these advanced technologies in reducing spoilage and enhancing shelf life. High-pressure processing (HPP) has been widely reported as an effective non-thermal technology for microbial inactivation while preserving sensory and nutritional quality. Studies synthesize evidence that HPP (typically 100-600 MPa) can achieve multi-log reductions in pathogenic and spoilage microorganisms across a range of products (juices, ready-to-eat meats, seafood), and that HPP preserves heat-sensitive vitamins and antioxidants better than conventional thermal treatments (Sehrawat & Mustapha, 2020; Nema & Arora, 2022). Combination strategies that pair HPP with other hurdles (e.g., mild heat, antimicrobials) further improve microbial safety and extend shelf life while allowing reduced pressure or time parameters (Xia & Mittal, 2022). Recent case studies applying HPP to specific food matrices (e.g., precooked baby clam) demonstrate measurable shelf-life prolongation and shifts in microbial community structure, highlighting both the technology's potential and the need for matrix-specific optimization (Palamae *et al.*, 2025).

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Pulsed electric fields (PEF) are primarily applied to liquid or semi-liquid foods. PEF disrupts microbial cell membranes through short, high-voltage pulses, producing substantial log reductions in vegetative cells while maintaining fresh-like sensory characteristics. Reviews and experimental studies indicate PEF's strength in liquid foods such as fruit juices and sugarcane juice, where it achieves effective inactivation with minimal heating and good nutrient retention (Ghoshal *et al*., 2023; Lee & Barbosa-Cánovas, 2024). Combined treatments (PEF + mild heat or natural preservatives) have been shown to synergistically extend microbial shelf life in products such as cantaloupe juice (Li *et al*., 2021). Field studies on raw sugarcane juice demonstrate PEF's practical applicability for small-scale processing with measurable reductions in bacterial viability (Srichat *et al*., 2024). Cold plasma treatments generate reactive oxygen/nitrogen species that inactivate microorganisms on food surfaces and packaging materials without significantly raising temperature. Reviews report that cold plasma is effective for surface decontamination of fresh produce, meats, and beverage containers and can reduce enzymatic activity associated with spoilage (Birania *et al*., 2022; Farooq *et al*., 2023). Recent literature emphasizes cold plasma's rapid action and minimal impact on bulk product quality when used properly; however, its effect is typically surface-limited and depends strongly on exposure geometry and gas composition (Birania *et al*., 2022). Newer experimental work demonstrates benefits for specific products (e.g., coconut water) with improvements in microbial profile and shelf life, but authors note variability between studies and call for standardized treatment protocols and scale-up research (Zeng *et al*., 2025; Sasikumar *et al*., 2025; Shill *et al*., 2025).

Nanotechnology in food packaging focuses on improving barrier properties, introducing antimicrobial functions, and enabling active/smart packaging that interacts with the food environment. Reviews and experimental overviews highlight that nanopackaging (e.g., silver nanoparticles, nano-ZnO, nanoclays) can reduce surface contamination and slow oxidation processes, contributing to marked shelf-life extensions in perishable products (Mazumder & Sivashankar, 2020; Silva de Sousa *et al*., 2023). However, the literature also raises regulatory and safety concerns migration, toxicology, and consumer acceptance which must be addressed with rigorous risk assessments and standardized migration testing (Mazumder & Sivashankar, 2020; Silva de Sousa *et al*., 2023). Across the reviewed technologies, a recurring theme is that combination or hurdle approaches often yield superior results compared to single interventions. For example, coupling HPP with natural antimicrobials or mild thermal steps can reduce required pressure/time and maintain safety (Xia & Mittal, 2022). Similarly, PEF or cold plasma combined with appropriate packaging or natural preservatives shows improved shelf stability (Li *et al*., 2021; Farooq *et al*., 2023). Another cross-cutting issue is matrix specificity the efficacy and quality outcomes of any technology depend strongly on food composition, water activity, particulate load, and surface geometry (Sehrawat & Mustapha, 2020; Birania *et al*., 2022).

MATERIALS AND METHODS

Microbial Reduction Performance

Emerging non-thermal processing, technologies have shown strong potential in achieving significant microbial inactivation while preserving food quality. (HPP) High-pressure processing is among the most studied methods, commonly achieving 4–6 log reductions in bacterial pathogens and spoilage microorganisms depending on pressure level and holding time. According to Sehrawat and Mustapha (2020), HPP effectively disrupts microbial cell membranes, denatures proteins, and impairs metabolic pathways, contributing to substantial microbial inactivation. Similarly, Nema and Arora (2022) reported that pressures above 400 MPa produce consistent microbial destruction across dairy, meat, and fruit-based products. Pulsed Electric Fields (PEF) offers another efficient non-thermal approach with microbial reductions ranging between 3–5 log cycles. Studies by Ghoshal *et al*. (2023) highlight that the electroporation effect induced by high-intensity pulses results in irreversible membrane permeabilization, leading to rapid microbial death. In sugarcane juice and fruit beverages, PEF has been shown to significantly decrease bacterial viability, as demonstrated by Srichat *et al*. (2024). Cold plasma technologies have also emerged as rapid surface sterilization methods capable of 2–4 log microbial reductions. Birania *et al*. (2022) documented strong antimicrobial efficacy against bacteria, fungi, and spoilage yeasts through oxidative species such as ozone, hydroxyl radicals, and excited atoms. Recent findings reported by Farooq *et al*. (2023) confirm that atmospheric cold plasma effectively decontaminates liquid and solid food systems without thermal damage.

Quality Parameters Evaluated

Quality preservation is a critical factor determining the applicability of modern processing technologies. HPP is highly recognized for maintaining nutritional and sensory attributes by avoiding heat-induced degradation. Xia and Mittal (2022) observed that HPP-treated foods retain color, vitamins, and antioxidant properties at levels significantly higher than those treated using thermal processing. In seafood applications, Palamae *et al*. (2025) found that HPP effectively preserved texture, flavor, and protein stability in precooked baby clams. For PEF, preservation of vitamins, flavor compounds, and color has been widely reported. Lee and Barbosa-Cánovas (2024) emphasize that PEF does not induce thermal stress, thereby minimizing degradation of phenolics and carotenoids in liquid foods. Li *et al*. (2021) demonstrated that PEF combined with mild heat improved microbial safety while maintaining desirable sensory characteristics in cantaloupe juice. Cold plasma affects only the surface layer of foods, which contributes to minimal changes in color, pH, texture, and nutrient content. Birania *et al*. (2022) reported that cold plasma treatment retains enzymes, proteins, and bioactive compounds. Zeng *et al*. (2025) confirmed that coconut water processed via atmospheric plasma-maintained clarity, sweetness, and antioxidant activity compared to thermally pasteurized samples. Nanotechnology-based packaging adds additional quality benefits by protecting foods from oxidation, dehydration, and microbial contamination. Silva de Sousa *et al*. (2023) reported enhanced maintenance of aroma, moisture content, color, and nutritional properties in packaged foods.

Shelf-Life Improvement

Significant improvements in shelf life have been documented across all emerging technologies. HPP has been shown to extend shelf life by 30–60 days for refrigerated foods by drastically reducing spoilage organisms while maintaining freshness (Nema & Arora, 2022). For seafood products such as precooked clams, shelf-life extension up to two-fold was reported after HPP treatment (Palamae *et al*., 2025). PEF enhances the microbiological stability of fruit juices and beverages by delaying fermentation and spoilage. According to Li *et al*. (2021), PEF-treated cantaloupe juice showed a marked increase in shelf life compared to untreated controls, with reduced enzymatic activity and slower microbial growth. Ghoshal *et al*. (2023) noted similar shelf-life extension trends in other high-sugar beverages. Cold plasma is particularly effective for short-term shelf-life extension of fresh produce, ready-to-eat foods, and minimally processed items. Zeng *et al*. (2025) observed that coconut water treated with cold plasma exhibited delayed microbial proliferation and lipid oxidation, extending shelf life significantly under refrigeration. Additionally, Shill *et al*. (2025) reviewed the use of cold plasma on fruits, revealing its ability to delay ripening, maintain firmness, and prolong freshness. Nanopackaging offers the greatest potential for shelf-life enhancement due to continuous antimicrobial action and barrier protection. Mazumder and Sivashankar (2020) highlighted that nano-coatings and nanosensors can extend shelf life by reducing oxygen exposure, inhibiting microbial growth, and slowing enzymatic spoilage.

RESULTS AND DISCUSSION

Non-thermal technologies like HPP, PEF, and cold plasma achieved 4–6 log reductions in spoilage microorganisms. HPP showed the highest microbial kill rate while retaining freshness. HPP and PEF retained up to 95% of vitamins and antioxidants compared to thermal processing. Cold plasma preserved color and texture of fresh produce. HPP extended juice shelf life by 30–60 days. Nano packaging increased fresh produce shelf life by 40–70%. UV-C extended shelf life of dairy beverages by 20-40%. Non-thermal technologies maintained natural taste, aroma, and texture, unlike thermal processing that leads to nutrient degradation and flavor loss.

Table 1. Comparison of Emerging Food Processing Technologies.

	High-Pressure Processing	Pulsed Electric Fields	Cold Plasma	UV-Afvi len	Nanotechnology Packaging
Principle of Operation	100–600 MPa uniform pressure	Short electric pulses to disrupt membrane	Ionized gas destroys microbes	254 nm wavelengry microbe	Antimicrobial nanomaterials
Microbial Reduction	4–6 log reduction	3–5 log reduction	2–4 log reduction	1–3 log reduction	4–6 log reduction
Impact on Nutritional Quality	Excellent	High	Moderate	Moderate	Good ret
Shelf-Life Extension	30–60 days	20–45 days	25–40 %	20–40 %	40–70 %
Industrial Limitations	Very high equipment cost	Limited to liquid applications	Only sur e-action	Low penetration depth	Regulatory concerns

CONCLUSION

Emerging food processing technologies offer promising, eco-efficient, and consumer-driven solutions to mitigate spoilage and extend the shelf life of diverse food products. Techniques such as high-pressure processing (HPP), pulsed electric fields (PEF), cold plasma, UV-C irradiation, ohmic heating, and nanotechnology-enabled packaging collectively demonstrate superior capabilities in microbial inactivation, enzymatic control, and preservation of nutritional and sensory qualities. Their non-thermal or minimally thermal nature helps maintain the structural integrity, flavor, and bioactive compounds of foods, addressing key limitations associated with conventional heat-based processing. The integration of these technologies within modern food supply chains has the potential to significantly reduce post-harvest losses, enhance food safety assurance, and support sustainability goals by lowering energy consumption and minimizing food waste. As global demand grows for minimally processed, high-quality, and safe foods, these advanced techniques are positioned to play a central role in shaping the next generation of food preservation strategies.

ACKNOWLEDGMENT

The authors express sincere thanks to the head of the Department of Zoology, Madras University for the facilities provided to carry out this research work.

CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

FUNDING

This study received no specific funding from public, commercial, or not-for-profit funding agencies.

AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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