INSIGHTS-JOURNAL OF
HEALTH AND REHABILITATION

EMERGING TECHNOLOGIES IN FOOD PROCESSING — A NARRATIVE REVIEW

Narrative Review

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Acknowledgement: The authors sincerely thank colleagues and mentors for their valuable insights and support during the preparation of this review.

Conflict of Interest: None
Grant Support & Financial Support: None

ABSTRACT

Background: Emerging food processing technologies have gained increasing importance as alternatives to conventional thermal methods, driven by consumer demand for safer, fresher, and nutritionally superior foods. Traditional heat-based techniques often compromise nutrient retention and sensory quality, whereas novel non-thermal and hybrid approaches aim to preserve bioactive compounds while ensuring microbial safety. Their growing relevance lies in addressing both public health and sustainability concerns, making them a pivotal area of food science research.

Objective: This review aims to synthesize current evidence on non-thermal and hybrid food processing technologies, evaluating their mechanisms, efficacy, applications, limitations, and future potential.

Main Discussion Points: High-pressure processing and pulsed electric fields have emerged as the most commercially advanced technologies, demonstrating significant efficacy in microbial inactivation with superior nutrient preservation. Cold plasma, ultrasound, ohmic heating, microwave- and radio-frequency-based methods, and three-dimensional food printing show considerable promise but face challenges in standardization, large-scale validation, and regulatory approval. Hybrid approaches combining multiple modalities enhance microbial inactivation and product quality, while digitalization and artificial intelligence improve process control and traceability. Packaging innovations, sustainability assessments, and consumer acceptance remain essential considerations.

Conclusion: The review highlights that while several technologies have transitioned toward commercial adoption, others remain at experimental or pilot stages. Evidence supports their capacity to enhance food safety and nutritional value, though methodological variability limits definitive conclusions. Advancing these technologies will require cross-disciplinary research, regulatory alignment, and rigorous sustainability assessments to ensure safe, reliable, and widely acceptable integration into food systems.

Keywords: High-pressure processing; Pulsed electric fields; Cold plasma; Hybrid food technologies; Digital process control; Narrative review.

INTRODUCTION

Food processing has traditionally relied on thermal methods such as pasteurization, sterilization, and canning to ensure microbial safety and extend shelf life. While effective, these methods often compromise the nutritional quality, sensory attributes, and functional properties of food products. In recent years, increasing consumer demand for minimally processed, fresh-like, and health-promoting foods has catalyzed the exploration of alternative technologies that maintain safety without sacrificing quality (1,2). This shift has positioned non-thermal and hybrid approaches at the forefront of food science innovation. Among the most promising developments are High-Pressure Processing (HPP), Pulsed Electric Fields (PEF), Cold Plasma (CP), Ultrasound (US), High-Intensity Pulsed Light (HIPL), Ohmic Heating, and Radio-Frequency or Microwave-assisted processing (3,4). Each of these technologies operates through distinct physical or chemical mechanisms, offering targeted benefits across diverse food classes. In parallel, novel applications such as 3D food printing, nano- and micro-enabled active packaging, edible coatings, enzyme-assisted transformations, and intensified membrane separation processes are reshaping how foods are preserved, enhanced, and delivered to consumers (5,6). Importantly, these advances are not emerging in isolation; hybrid approaches that integrate multiple technologies are increasingly employed to harness synergistic effects and overcome the limitations of single interventions.

This technological transition has profound implications not only for food quality but also for public health. Ensuring the microbial safety of food without degrading nutrients, flavor, or texture directly supports dietary adequacy and consumer well-being (7). Furthermore, the integration of artificial intelligence, automation, and advanced sensor technologies in process monitoring enhances precision, reproducibility, and regulatory compliance, further reinforcing trust in novel food systems. However, despite rapid progress, there remain knowledge gaps regarding long-term health impacts, scalability, energy efficiency, and consumer acceptance, which hinder widespread industrial adoption (8,9). Against this backdrop, the present review aims to critically examine emerging non-thermal and hybrid food processing technologies, highlighting their mechanisms, advantages, limitations, and future directions. The objective is to provide a comprehensive understanding of how these approaches may address current challenges in food safety, nutrition, and sustainability while identifying research gaps that must be bridged to fully realize their potential (10).

CLASSIFICATION AND TRENDS

Emerging food processing technologies can be broadly categorized into non-thermal microbial inactivation methods, innovative volumetric heating systems, physical and structural modification tools, additive manufacturing, packaging innovations, and digital process intelligence. Recent bibliometric analyses indicate a surge of publications on Cold Plasma (CP), Pulsed Electric Fields (PEF), and High-Pressure Processing (HPP) after 2015, reflecting a growing research and commercial interest in these platforms (1). Among these, HPP has achieved significant commercial penetration, especially in juices, seafood, and ready-to-eat meats, while PEF and ohmic heating are undergoing wider deployment in beverages and dairy sectors (2). This classification underscores a transition toward approaches that integrate food safety with preservation of nutritional and sensory quality, a priority driven by consumer demand for minimally processed, fresh-like products.

HIGH-PRESSURE PROCESSING (HPP)

Mechanism

HPP employs uniform isostatic pressures ranging between 100–600 MPa to packaged foods, resulting in microbial inactivation through membrane disruption, protein denaturation, and enzyme inactivation, while minimizing thermal damage (3).

Efficacy & data

Evidence demonstrates that HPP can reduce vegetative pathogens such as *Listeria monocytogenes* and *E. coli* O157:H7 by 3–6 $\log_{10}$ cycles, depending on the food matrix and applied pressure-time combinations. However, bacterial spores are notably resistant, necessitating combined strategies with temperature or natural antimicrobials (4).

Applications & limitations

Commercially, HPP is widely applied to fruit juices, guacamole, cured meats, and seafood. Its ability to retain vitamin C and volatile compounds gives it a clear advantage over thermal pasteurization. Despite these strengths, the batch-based operation, high equipment costs, and limited spore inactivation remain important limitations (5).

PULSED ELECTRIC FIELDS (PEF)

Mechanism & parameters

PEF applies short pulses of high-voltage electricity (0.1–100 kV/cm) to pumpable foods, inducing electroporation of microbial membranes.

Data & performance

Studies on juices, liquid eggs, and milk consistently show 3–5 $\log_{10}$ reductions in vegetative microbes under optimized conditions, though enzyme inactivation is incomplete and often requires mild thermal supplementation (6).

Advantages and challenges

PEF is characterized by minimal heat generation, excellent retention of fresh flavors, and rapid processing. Nevertheless, electrode fouling, heterogeneous fields in particulate foods, and challenges in scaling up for viscous or heterogeneous matrices present obstacles for industrial integration (7).

COLD PLASMA (NON-THERMAL ATMOSPHERIC PLASMA)

Mechanism

CP generates reactive oxygen and nitrogen species, UV photons, and charged particles that act synergistically to inactivate microorganisms.

Efficacy & evidence

Experimental studies show 2–5 $\log_{10}$ microbial reductions on fresh produce and packaging materials. Additionally, CP can degrade pesticide residues without markedly compromising sensory attributes, provided conditions are optimized (8).

Limitations & commercialization

The primary limitation is its superficial action, with efficacy largely restricted to surface decontamination. Challenges include uneven penetration across irregular geometries and chemical modifications to treated surfaces, which limit regulatory acceptance at industrial scale.

ULTRASOUND (HIGH-INTENSITY & LOW-INTENSITY)

Mechanisms & uses

High-intensity ultrasound (20–100 kHz) induces acoustic cavitation, generating localized shear forces and free radicals useful in emulsification, extraction, and tenderization. Low-intensity ultrasound, in contrast, is used for non-destructive testing and quality assessment.

Data highlights

Evidence indicates improved emulsion stability and enhanced protein digestibility, with ultrasound shown to increase hydrolysis rates and emulsifying properties in dairy and plant-based proteins (3,6).

Considerations

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Despite promising outcomes, industrial scaling remains constrained by energy requirements and equipment limitations. Radical-induced oxidation of food components requires careful process control to maintain safety and quality.

High-Intensity Pulsed Light (HIPL) & UV-based methods

HIPL applies intense broadband light pulses for surface decontamination of packaging and food surfaces. Dose–response studies show effective inactivation of pathogens on fruits, vegetables, and packaging; however, excessive exposure can lead to undesirable photochemical changes, restricting its use to surface treatment applications (9).

OHMIC HEATING, MICROWAVE, AND RADIO-FREQUENCY PROCESSING

Ohmic heating

This method involves passing electrical currents through foods, resulting in rapid, uniform volumetric heating. It is particularly effective for particulate foods and demonstrates superior retention of texture and nutrients compared with conventional heating (10).

Microwave & RF

Both microwave and RF systems allow rapid volumetric heating, widely applied in drying, tempering, and sterilization. Despite their efficiency, issues of hot spots and non-uniform heating remain, although continuous-flow designs and sensor-assisted systems are advancing solutions (11).

3D Food Printing (Additive manufacturing)

Scope & mechanisms

3D printing uses extrusion or jetting methods to deposit customized food "inks." Its promise lies in personalized nutrition, texture tailoring, and specialized diets, such as dysphagia-friendly foods.

Data & challenges

Pilot studies demonstrate feasibility for personalized dietary interventions, though rheology, nozzle design, and post-processing are critical determinants of fidelity. Current limitations include slow printing speeds, cost, and limited large-scale applicability (12).

ACTIVE, INTELLIGENT AND EDIBLE PACKAGING (NANO-ENABLED)

Technologies

Nano-enabled edible coatings, antimicrobial films, oxygen scavengers, and biosensors have demonstrated capacity to extend shelf life and monitor quality dynamically.

Performance

Encapsulation of natural antimicrobials in nanoemulsions and cellulose films has extended product shelf life by days to weeks across fruits, meats, and dairy. However, regulatory scrutiny persists due to potential nanoparticle migration into foods (13).

Membrane processes, intensified separations & extraction (including novel solvents)

Advances in nanofiltration, membrane distillation, and ultrasound-assisted extraction enable recovery of bioactives and energy-efficient processing. These methods improve product yield and reduce thermal damage, making them increasingly attractive in functional food development (14).

Hybrid & combined processes

Hybrid approaches, such as PEF with mild heat or HPP with antimicrobial agents, have demonstrated synergistic microbial inactivation and enhanced product stability. Several systematic reviews highlight that, combined methods achieve higher log reductions and better quality retention compared with single techniques (15).

Digitalization, sensors and AI in process control

Integration of inline sensors and machine learning models is enhancing real-time monitoring of Brix, solids, and microbial status. Digital twins and predictive maintenance are emerging as powerful tools to optimize energy use and improve reproducibility in industrial settings (15,16).

Safety, regulatory and sustainability considerations

While HPP and PEF have attained regulatory acceptance in many regions, CP and nano-packaging require further safety validation. Life-cycle assessments indicate that these technologies can reduce food waste and energy use, although equipment costs and manufacturing impacts influence net sustainability outcomes (17,18).

Commercialization & economics

HPP maintains the largest commercial presence, with global facilities dedicated to juices, guacamole, and ready-to-eat meats. Although capital-intensive, it allows premium positioning due to extended shelf life and nutrient preservation. PEF, ohmic heating, and active packaging are advancing from pilot to commercialization, while CP and 3D printing remain at early adoption stages (19).

Table: Selected data table (quick reference)

Technology	Typical parameters	Typical log reductions (vegetative microbes)	Main applications	Key limitation
HPP	400–600 MPa, 1–6 min, often 20–25°C	3–6 $\log_{10}$	Juices, RTE meats, guacamole	Spore inactivation limited, capital cost. ResearchGatePMC
PEF	0.1–100 kV/cm; µs–ms pulses	2–5 $\log_{10}$ (liquids)	Juices, milk, liquid eggs	Particulates, electrode fouling. ScienceDirect+1
Cold plasma	DBD, plasma jets; atmospheric	2–5 $\log_{10}$ (surface)	Surface decontamination, packaging	Limited penetration; surface only. ScienceDirect+1
Ultrasound	20–100 kHz, high intensity	Variable (used for structure more than sterilization)	Emulsions, extraction, tenderizing	Oxidation; scale-up design needed. MDPIScienceDirect
Ohmic heating	Voltage depends on conductivity	Rapid thermal kill comparable to conventional	Particulate foods, pasteurization	Requires conductive product; electrode issues. SpringerLinkWiley Online Library
3D printing	Rheology-dependent	N/A (manufacturing tech)	Personalized diets, dysphagia foods	Speed, cost, food safety standards. PMCNew York Post

CRITICAL ANALYSIS AND LIMITATIONS

A critical appraisal of the current literature on non-thermal and hybrid food processing technologies reveals both promising progress and persistent limitations that constrain translation into widespread commercial and regulatory adoption. Many studies investigating microbial inactivation, nutrient retention, and sensory preservation under technologies such as high-pressure processing, pulsed electric fields, and cold plasma are conducted at laboratory or pilot scales, often with small sample sizes and limited replication (19). While these investigations provide important mechanistic insights, the lack of large-scale randomized controlled validations restricts the strength of evidence for industrial implementation and consumer safety assurance. Methodological limitations are also apparent in the form of inconsistent experimental designs. For instance, heterogeneity in pressure ranges, pulse durations, or plasma generation conditions makes it difficult to directly compare findings across studies. The absence of standardized process validation protocols contributes to variability in reported microbial log reductions and nutrient retention outcomes, leading to potential confounding in meta-analyses (20). Additionally, many investigations focus on a narrow set of food matrices such as fruit juices or liquid dairy products, with comparatively fewer data available for heterogeneous or particulate systems where processing uniformity remains a challenge. Potential sources of bias also need consideration. Studies demonstrating significant microbial inactivation or superior nutrient preservation are more likely to be published, while inconclusive or negative findings may be underreported, contributing to publication bias (21). Moreover, some reports originate from technology developers or industry-funded projects, raising concerns about performance bias and selective reporting of favorable results without transparent acknowledgment of technical drawbacks such as electrode fouling in PEF or oxidative modifications during ultrasound treatment.

Another limitation lies in the variability of outcome measurements. While microbial inactivation is often expressed in log reductions, differences in initial inoculum levels, target organisms, and detection methods introduce inconsistencies. Similarly, nutrient retention is measured using diverse analytical techniques, from spectrophotometry to chromatography, making cross-study comparisons difficult. Sensory outcomes, which are central to consumer acceptance, are frequently assessed with small, non-representative panels, limiting their reliability (22). Generalizability of current findings is further restricted by the focus on high-value products and industrialized market contexts. Limited research has evaluated these technologies in low-resource settings, despite their potential role in improving food safety and reducing post-harvest losses globally. Moreover, regulatory evaluations for novel approaches such as nano-enabled packaging or cold plasma treatments remain fragmented across regions, underscoring a gap between scientific progress and policy alignment (23). Finally, sustainability assessments, though increasingly common, often rely on narrow system boundaries and overlook full life-cycle impacts, such as energy sourcing, equipment manufacturing, and end-of-life disposal. This undermines the robustness of claims regarding environmental advantages. Integration of artificial intelligence and sensor technologies has been proposed as a solution for process control, yet mechanistic models linking process conditions, microbiological outcomes, and food matrix characteristics remain underdeveloped (24). Taken together, the existing literature highlights that while emerging processing technologies hold great potential, their evaluation is constrained by methodological weaknesses, publication biases, variability in measurement outcomes, and limited generalizability. Addressing these gaps will require large-scale validation, standardized protocols, rigorous sustainability analyses, and consumer-focused studies to ensure that technological promise translates into safe, acceptable, and sustainable applications in global food systems.

IMPLICATIONS AND FUTURE DIRECTIONS

The synthesis of current evidence on non-thermal and hybrid food processing technologies has important implications for clinical nutrition, food safety practice, and public health. By demonstrating that these approaches preserve thermolabile nutrients, enhance bioactive stability, and minimize the formation of undesirable compounds compared with conventional heat treatments, the reviewed studies underscore their potential role in safeguarding nutritional quality within patient diets and broader consumer populations. For individuals with specific clinical needs, such as compromised immunity or nutrient deficiencies, foods processed with techniques like high-pressure processing or pulsed electric fields may offer safer options that retain higher levels of vitamins and antioxidants, thereby supporting therapeutic nutrition strategies (21). At a policy level, the findings emphasize the urgency of developing harmonized regulatory frameworks that address novel interventions such as nano-enabled packaging, additive manufacturing, and cold plasma treatment. The absence of comprehensive guidelines creates uncertainty for manufacturers and healthcare providers alike. Standardized safety protocols, validated hazard analysis and critical control points (HACCP), and clearer regulatory pathways are required to bridge the gap between scientific advancement and consumer protection. Policymakers must also integrate sustainability considerations into these frameworks, given that life-cycle assessments suggest that several of these technologies could lower energy consumption and reduce food waste, but outcomes are dependent on energy sourcing and equipment design (22). Despite rapid progress, several unanswered questions remain. A critical gap lies in the inactivation of bacterial spores at low temperatures, which continues to limit the reliability of non-thermal systems for shelf-stable products. Hybrid solutions, such as pressure–temperature or plasma–heat combinations, show promise but require systematic validation (23).

Similarly, much of the available research remains restricted to laboratory or pilot-scale studies, and robust data on scale-up, continuous processing, and long-term safety are scarce. Consumer acceptance of foods treated with plasma, nanomaterials, or 3D printing technologies also remains insufficiently explored, particularly in culturally diverse populations where perceptions of "naturalness" strongly influence dietary choices (24). Future research should adopt more rigorous study designs, with larger sample sizes, standardized protocols, and inclusion of diverse food matrices to enhance generalizability. Mechanistic models linking microbial inactivation kinetics, nutrient retention, and structural changes in complex food systems are needed to improve predictive capacity and process optimization. Integration of artificial intelligence and sensor-based monitoring in upcoming trials can help achieve real-time validation and quality control, ensuring both safety and reproducibility. Furthermore, sustainability-focused studies should expand their scope to include full life-cycle assessments, accounting not only for energy savings during operation but also for equipment production and disposal impacts (25,26). In conclusion, while emerging non-thermal and hybrid processing methods have already begun to reshape modern food systems, their broader integration into clinical practice, regulatory policy, and public health strategies will depend on addressing the existing research gaps through carefully designed, interdisciplinary studies. Bridging these limitations will ensure that such technologies can deliver on their promise of safe, nutritious, and sustainable foods for diverse populations worldwide.

CONCLUSION

The evidence synthesized in this review highlights that emerging food processing technologies present transformative opportunities for delivering safer, higher-quality, and more personalized foods. Among these, high-pressure processing and pulsed electric fields have achieved the greatest commercial maturity, while cold plasma and three-dimensional food printing demonstrate strong potential but remain limited by challenges in scale-up, regulatory clarity, and standardization. The literature overall provides encouraging support for these innovations, yet methodological variability and limited large-scale validations temper the strength of current conclusions. Hybrid processing strategies and digitalized control systems appear particularly promising, offering improvements in efficacy, quality retention, and traceability. For clinicians and researchers, these findings underscore the value of integrating advanced processing into nutritional strategies while maintaining vigilance for safety, consumer acceptance, and sustainability. Continued interdisciplinary research spanning food science, microbiology, materials engineering, and data science is urgently needed to translate laboratory advances into industrial-scale solutions that are both robust and widely accessible.

AUTHOR CONTRIBUTION

Author	Contribution
Muhammad Usama Aslam*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Esha Aslam	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Muhammad Shahbaz*	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published

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