

Innovative Non-Thermal and Advanced Processing Technologies for Optimizing Nutrient Retention and Extending Food Shelf Life: Integration of Machine Learning for Process Optimization

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ABSTRACT: Conventional thermal processing methods such as drying, salting, fermentation, pasteurization, and sterilization remain the backbone of food processing and preservation. However, heat-induced losses of vitamins, pigments, bioactive compounds, and texture quality often compel manufacturers to explore alternative approaches to satisfy

evolving consumer demands. In response to the increasing preference for minimally processed foods that retain nutritional quality and fresh-like characteristics, researchers and industry stakeholders have turned to innovative non-thermal and advanced processing technologies. This comprehensive review evaluates the current landscape of non-thermal technologies, including high hydrostatic pressure (HHP), pulsed electric field (PEF), ultrasonication (US), cold plasma (CP), UV irradiation (UVC), and ozonation, that effectively inactivate spoilage and pathogenic microorganisms while operating at ambient or modest temperatures. Additionally, recent advances in artificial intelligence (AI) and machine learning (ML) optimization for these technologies are explored, highlighting their potential to enhance process efficiency, predict microbial inactivation kinetics, and optimize nutritional retention. These methods preserve sensory qualities, improve technological properties, support better digestibility and oxidative stability, and significantly extend shelf life across various food matrices with minimal thermal degradation.

Keywords: *Food processing, non-thermal technologies, hydrostatic pressure, ultrasonication, ozonation, oxidative stability, machine learning, artificial intelligence, process optimization*

1. Introduction

Food processing is an integral component of modern food systems, playing a crucial role in ensuring food safety, extending shelf life, maintaining nutritional quality, improving palatability, and enhancing convenience for consumers (Jyoti et al., 2025). Historically, traditional food processing methods such as drying, salting, fermentation, pasteurization, sterilization, and evaporation have been widely used to ensure the microbial safety of food and extend shelf life (Huebbe and Rimbach, 2020). However, these methods often compromise heat-sensitive nutrients like vitamins, bioactive compounds, and natural flavours, leading to reduced nutritional value and sensory degradation (Ağagündüz et al., 2025). In addition, excessive heat may alter protein structure, reduce amino acid availability, promote lipid oxidation, and negatively affect colour, flavour, and texture. While chemical preservatives and intensive processing techniques can enhance shelf stability, growing concerns regarding their long-term health effects and consumer perception have further intensified the demand for alternative approaches (Jyoti et al., 2025).

In response to evolving consumer demand for minimally processed foods that retain nutritional quality and fresh characteristics, researchers and industry stakeholders have turned to innovative non-thermal and advanced processing technologies. These non-thermal processing technologies use physical mechanisms other than heat to inactivate microorganisms and enzymes that cause spoilage, thereby preserving nutritional quality and extending food shelf life. Unlike conventional thermal methods, non-thermal techniques minimize thermal damage to food components, enabling better retention of heat-sensitive nutrients such as vitamins, antioxidants, proteins, and phytochemicals. These technologies offer promising solutions to extend shelf life while preserving or enhancing nutrient retention, safety, and product quality (Zhang et al., 2019).

Recent technological advancements have witnessed the integration of artificial intelligence (AI) and machine learning (ML) algorithms in optimizing non-thermal food processing operations. The complex, non-linear interactions between ingredients and processing conditions, combined with variability in raw materials and environmental factors, necessitate sophisticated modelling approaches beyond traditional mathematical frameworks (Rashvand et al., 2025). ML-based modelling can effectively predict process kinetics and optimize process parameters efficiently for ensuring better-quality products while handling large datasets more effectively than conventional methods (Khan et al., 2024). Figure 1 illustrates the key non-thermal technologies and their integration with AI-driven optimization systems, representing a paradigm shift toward intelligent, data-driven food processing systems.

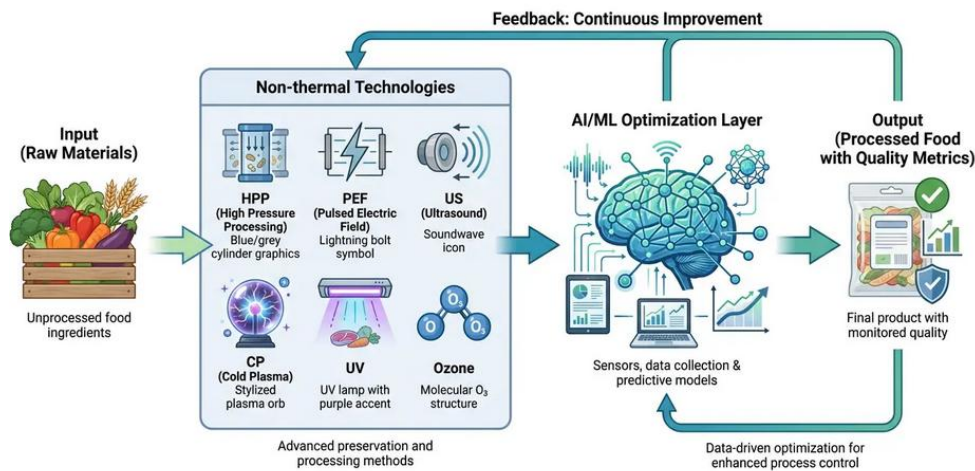


Figure 1. Schematic representation of non-thermal food processing technologies integrated with AI-driven optimization. The diagram shows the interconnections between HPP, PEF, ultrasonication, cold plasma, UV irradiation, ozonation, and machine learning algorithms for real-time process control and quality prediction

2. Key Non-Thermal and Advanced Technologies for Food Processing

2.1 High-Pressure Processing (HPP)

High-Pressure Processing (HPP), also referred to as high hydrostatic pressure (HHP), offers the food industry a unique opportunity to develop new foods of improved nutritional and sensory quality, novel texture, more convenience, higher safety, and increased shelf-life than conventionally-processed products (Knorr et al., 2002). HPP involves subjecting food products to extremely high pressures (typically 100-900 MPa) uniformly transmitted from all directions for a short duration through a pressure-transmitting medium, usually water, without significant increases in temperature. This disrupts microbial membranes and deactivates spoilage enzymes while preserving sensory and nutritional attributes.

The market for HPP technology has experienced remarkable growth, with the global market value standing at approximately USD 9.8 billion in 2015 and projected to reach USD 54.77 billion by 2025, driven by an average production growth of 500,000 tons annually across North America, Europe, and Asia (Leong et al., 2024; Keewan et al., 2025). However, HPP processing costs remain higher than traditional thermal pasteurization, at approximately 10.7 US¢/L for orange juice compared to 1.5 US¢/L for thermal pasteurization (Keewan et al., 2025).

HPP affects non-covalent bonds that are sensitive to pressure. However, small molecules with covalent bonds, such as those responsible for color and bioactive properties, are generally less affected by pressure (Sehrawat et al., 2021). Recent studies have shown that HHP is effective not only in microbial inactivation but also in increasing antioxidant capacity, preservation or liberation of bioactive components such as polyphenols, flavonoids as well as vitamins (Athira et al., 2023). Table 1 summarizes the effects of HPP on quality parameters in different food products, demonstrating its versatility across various food matrices.

Food Product	Quality Parameter	Effects of High-Pressure Processing (HPP)
Fruits and vegetables	Nutritional content and colour	Minimizes nutrient loss, especially heat-sensitive vitamins and antioxidants; preserves natural colour and flavour; maintains fresh-like texture

Meat and seafood products	Nutrient retention and microbial safety	Effectively inactivates pathogens (<i>E. coli</i> , <i>Listeria</i> , <i>Salmonella</i>); extends shelf life by 50-150%; retains natural texture and juiciness; preserves protein integrity
Dairy products	Texture and microbial safety	Eliminates harmful microorganisms without heat damage; preserves creamy texture; maintains protein functionality and calcium bioavailability; extends shelf life by 2-4 weeks
Beverages and juices	Sensory quality and bioactive compounds	Retains fresh flavour profile; preserves vitamin C, polyphenols, and anthocyanins; achieves 5-log pathogen reduction; extends shelf-life 21-150 days under refrigeration

2.2 Pulsed Electric Field (PEF)

Pulsed Electric Field (PEF) technology represents a non-thermal food preservation method that applies short-duration high-voltage electrical pulses to liquid or semi-liquid foods placed between two electrodes. The electric field intensity typically ranges from 10 to 80 kV/cm with pulse durations in microseconds (Bazhal et al., 2019). This treatment causes electroporation of microbial cell membranes, leading to irreversible membrane damage and subsequent microbial inactivation.

PEF technology has demonstrated the ability to achieve 4-6 log cycle reductions of foodborne pathogens and spoilage microorganisms at temperatures below those typically used in traditional heat pasteurization (Wan et al., 2024). The technology is particularly effective for preserving fruit juices and beverage products, with studies showing 5.44-5.09 log reductions of *Lactobacillus brevis* and *Listeria innocua* in PEF-treated fruit juice-soymilk blends (Morales-de la Peña et al., 2010). The United States FDA has acknowledged PEF technology for achieving 5-log reductions of pathogenic bacteria in fruit juices (Leong et al., 2024).

Beyond microbial inactivation, PEF enhances extraction efficiency of bioactive compounds and improves mass transfer processes. Studies have demonstrated that PEF-

assisted extraction can increase yields of phenolic compounds, anthocyanins, and other phytochemicals while reducing extraction time and solvent consumption (Kulawik et al., 2023). However, optimization of PEF parameters is critical, as poor settings can result in inadequate microbial inactivation or degradation of sensitive nutrients due to non-uniform electric field distribution (Rashvand et al., 2025).

2.3 Ultrasonication (US)

Ultrasonication employs high-frequency sound waves (typically 20-100 kHz) to generate cavitation bubbles in liquid media. The rapid formation and collapse of these bubbles create localized regions of extreme temperature (up to 5000 K) and pressure (up to 500 MPa) that disrupt microbial cell structures (McClements, 1995; Piyasena et al., 2003). This acoustic cavitation phenomenon provides effective microbial inactivation while operating at ambient temperatures.

Recent advances in multifrequency ultrasound technology have shown particular promise in addressing challenging targets such as bacterial spores. Wahia et al. (2024) demonstrated that multifrequency ultrasound application can effectively inactivate and germinate *Alicyclobacillus acidoterrestris* spores in juice products, representing a significant advancement in juice industry applications. Beyond microbial control, ultrasonication enhances mass transfer, particle size reduction, and enzyme activity modulation (Speranza et al., 2021; Mukhtar et al., 2022).

Machine learning algorithms, particularly support vector machines (SVM) and least squares-SVM (LS-SVM), have been successfully applied to optimize ultrasound-assisted extraction processes. These models demonstrate higher accuracy in predicting and optimizing extraction parameters for bioactive components with antioxidant activity compared to traditional empirical approaches (Liao et al., 2016; Kunjiappan et al., 2024).

2.4 Cold Plasma (CP)

Cold plasma, particularly atmospheric-pressure cold plasma (APCP), has emerged as a promising non-thermal method for microbial decontamination of food products and food-contact surfaces. In cold plasma generation, gases are exposed to high energy, creating a non-thermal state in which electrons reach extremely high temperatures (up to tens of thousands of Kelvin), whereas neutral molecules and radicals remain at room temperature (Keewan et al., 2025). This unique property enables the inactivation of microorganisms

without damaging the underlying materials, making it an attractive tool for processing heat-sensitive food products.

The antimicrobial mechanism of cold plasma involves multiple reactive species, including reactive oxygen species (ROS), reactive nitrogen species (RNS), ultraviolet photons, and charged particles. These species work synergistically to disrupt microbial cell membranes, denature cellular proteins, and damage nucleic acids (Harikrishna et al., 2023). Recent studies have demonstrated synergistic effects when cold plasma is combined with essential oils, achieving enhanced antimicrobial activity against biofilms on food-contact surfaces (Cui et al., 2016).

Emerging research has shown that APCP treatment can provide positive sensory enhancements. Kumar et al. (2024) demonstrated superior sensory quality in kiwifruit juice following optimized plasma treatments compared to conventional thermal processing, with improvements in color brightness and desirable aroma attributed to enzyme modulation and pigment stabilization. Furthermore, plasma-activated water (PAW) has gained attention for its potential in safe and sustainable food production, offering advantages in surface decontamination and functional property modification (Zou et al., 2025).

2.5 UV Irradiation and Ozonation

UV-C irradiation (200-280 nm wavelength) and ozonation represent oxidative non-thermal technologies that effectively reduce microbial loads through distinct mechanisms. UV-C light causes direct DNA damage through thymine dimer formation, preventing microbial replication, while ozone (O_3) exerts its antimicrobial effect through powerful oxidation of cellular components (Baggio, 2020). Both technologies are particularly effective for surface decontamination and liquid food treatment.

Ozone has been confirmed to be highly effective in both reducing microbial contamination and removing pesticide residues in studies on fruits, vegetables, cereals, meat products, and packaging surfaces (Arslan et al., 2025). The ozone gas denatures proteins and microbial DNA by interacting with amino acids, resulting in cell death. However, both UV-C and ozone treatments require careful parameter control to minimize potential degradation of photosensitive vitamins and bioactive compounds. Table 2 presents a comparative analysis of all non-thermal technologies discussed, including their mechanisms, advantages, limitations, and typical applications.

Technology	Mechanism	Advantages	Limitations	Applications
HPP	High pressure (100-900 MPa) disrupts microbial membranes and deactivates enzymes	Preserves nutrients, flavor, color; uniform treatment; effective microbial inactivation	High cost; ineffective against spores; batch processing	Juices, RTE meals, dairy, seafood
PEF	High voltage pulses (10-80 kV/cm) cause cell membrane electroporation	Short processing time; energy efficient; enhances extraction; 4-6 log reduction	Limited to liquid/semi-liquid; electrode fouling; non-uniform field	Juices, liquid eggs, milk, extraction
Ultrasound	Acoustic cavitation (20-100 kHz) disrupts cells; localized hot spots	Mass transfer enhancement; particle size reduction; enzyme modulation	Energy intensive; limited penetration depth; equipment cost	Extraction, emulsification, defoaming, cutting
Cold Plasma	Reactive species (ROS, RNS), UV photons, charged particles damage cells	Low temperature; surface decontamination; sensory enhancement; environmental friendly	Surface treatment only; equipment complexity; gas requirements	Fresh produce, meat surfaces, packaging
UV-C	DNA damage via thymine dimer formation (200-280 nm)	Chemical-free; fast; effective for liquids and surfaces	Limited penetration; shadowing effects; vitamin degradation	Water, juices, air, surface sanitation
Ozonation	Strong oxidation of proteins and DNA; membrane disruption	Broad spectrum; pesticide removal; decomposes to oxygen; no residue	Short half-life; must be generated on-site; potential off-flavour	Washing produce, water treatment, storage

3. Integration of Artificial Intelligence and Machine Learning in Non-Thermal Processing

The integration of AI and ML technologies represents a paradigm shift in non-thermal food processing optimization. Traditional empirical models rely on limited experimental data and struggle to capture the complex, non-linear interactions between ingredients, processing conditions, and environmental factors (Rashvand et al., 2025). In contrast, ML models trained on vast amounts of multi-dimensional data can precisely capture these interactions and provide accurate predictions for process optimization.

3.1 Machine Learning Algorithms for Process Optimization

Several ML algorithms have demonstrated effectiveness in optimizing non-thermal processing parameters:

Artificial Neural Networks (ANNs) have shown particular success in HPP applications. Chakraborty et al. (2019) developed models combining ANN with kinetic approaches to predict pectin methylesterase inactivation trends in pineapple puree during HPP. Liu et al. (2022) utilized backpropagation neural networks (BPNN) to predict antioxidant capacity in not-from-concentrate peach and carrot juice blends, enabling real-time process monitoring and control.

Support Vector Machines (SVM) and their variants have proven effective for ultrasound-assisted extraction optimization. Yu et al. (2025) demonstrated that SVM models improved by 9.68% after first-order derivatives preprocessing in terahertz imaging applications for food quality monitoring. The LS-SVM model showed higher efficiency in analyzing and optimizing ultrasound-assisted extraction of bioactive components (Liao et al., 2016).

Random Forest (RF) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have been applied to predict antimicrobial activity of plasma-activated liquids and optimize extraction parameters. Kunjiappan et al. (2024) successfully maximized bioactive ingredient extraction from grape seeds using ultrasound-aided extraction with ANFIS and RF optimization.

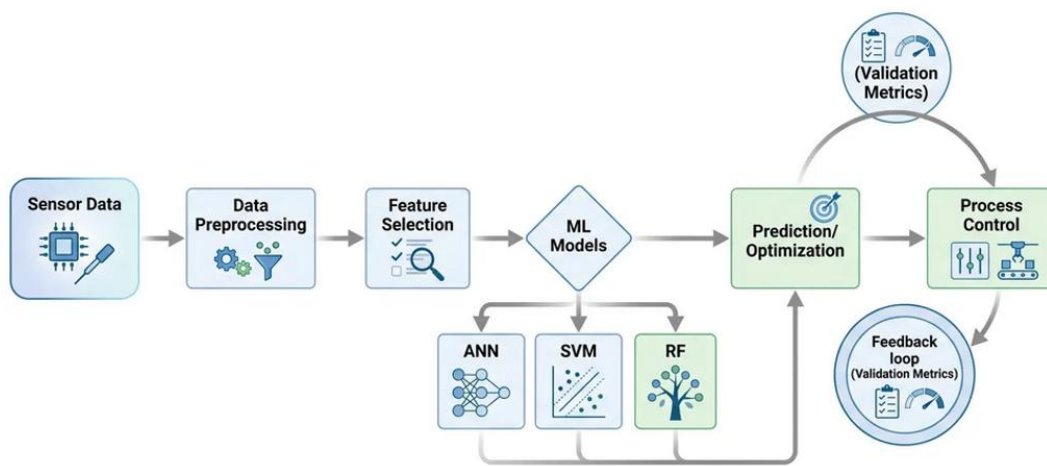


Figure 2. Machine learning workflow for non-thermal food processing optimization. The diagram illustrates data collection from sensors, feature extraction, model training (ANN, SVM, RF, ANFIS), real-time prediction, and feedback control mechanisms.

Source: Adapted from Rashvand et al. (2025).

4. Impact on Nutrient Retention and Shelf Life

Advanced food processing and packaging technologies have a significant impact on both the nutritional quality and shelf stability of food products. Numerous studies highlight that non-thermal technologies effectively retain or enhance nutrient stability in various food matrices. For example, non-thermal methods show higher retention of ascorbic acid and antioxidants compared to conventional heat treatments (Arslan et al., 2025). These technologies also mitigate nutrient loss in sensitive bioactive compounds, supporting improved functional and nutritional quality.

In addition to nutrient preservation, innovative non-thermal processing has been shown to significantly extend product shelf life by effectively reducing microbial load and slowing spoilage pathways. This is particularly evident in liquid foods, where microbial stability and quality attributes can be maintained for extended periods under refrigeration following non-thermal treatment. HPP-treated fruit juices have demonstrated shelf lives ranging from 21 to 150 days under refrigeration while maintaining fresh-like sensory quality (Leong et al., 2024).

The limitations associated with individual treatments can be addressed using a combination of innovative non-thermal processing technologies to enhance shelf life and retention of bioactive compounds (Arslan et al., 2025). For instance, complete inactivation of microbial spores such as *Bacillus pumilus* can be achieved using combinations of supercritical carbon

dioxide with co-solvents or antimicrobial peptides (Keewan et al., 2025). Table 3 presents quantitative data on nutrient retention and shelf-life extension achieved with various non-thermal technologies compared to thermal processing.

Technology	Vitamin C Retention (%)	Antioxidant Retention (%)	Shelf Life Extension (days)
Thermal Pasteurization (Control)	45-60	50-65	7-14
HPP (600 MPa, 5 min)	85-95	90-98	21-150 (refrigerated)
PEF (35 kV/cm)	80-92	85-93	14-45 (refrigerated)
Ultrasonication (40 kHz)	75-88	80-90	10-30 (refrigerated)
Cold Plasma (10 min)	88-96	92-98	7-21 (refrigerated)
Combined (HPP + PEF)	92-98	95-99	60-180 (refrigerated)

5. Challenges and Future Prospects

Despite clear advantages, widespread adoption of non-thermal and advanced processing technologies faces several challenges. High operational costs, scalability issues, and varying regulatory frameworks are significant barriers to large-scale implementation. The capital investment required for HPP equipment and operational costs remain substantially higher than conventional thermal processing, with processing costs approximately 7-fold higher for HPP compared to thermal pasteurization (Keewan et al., 2025).

Optimizing process parameters for specific food matrices is critical to maximizing nutrient retention and safety outcomes. The complex interactions between food components and processing conditions require sophisticated optimization approaches. ML-driven monitoring systems with integrated sensors and real-time data accumulation show promise in enhancing process efficiency while accounting for the inherent variability in food matrices (Rashvand et al., 2025).

There is also a need to increase consumer awareness and regulatory guidance to foster acceptance of these technologies. Future research should focus on:

- Synergistic combinations of non-thermal methods (e.g., HPP + PEF, US + ozone) to further enhance nutrient retention and shelf life while reducing energy use and environmental impact
- Development of advanced ML models and intelligent systems for real-time process control and optimization
- Life-cycle assessments and techno-economic evaluations to support industrial scalability
- Development of functional and enriched food products tailored for specific health outcomes using combined non-thermal strategies

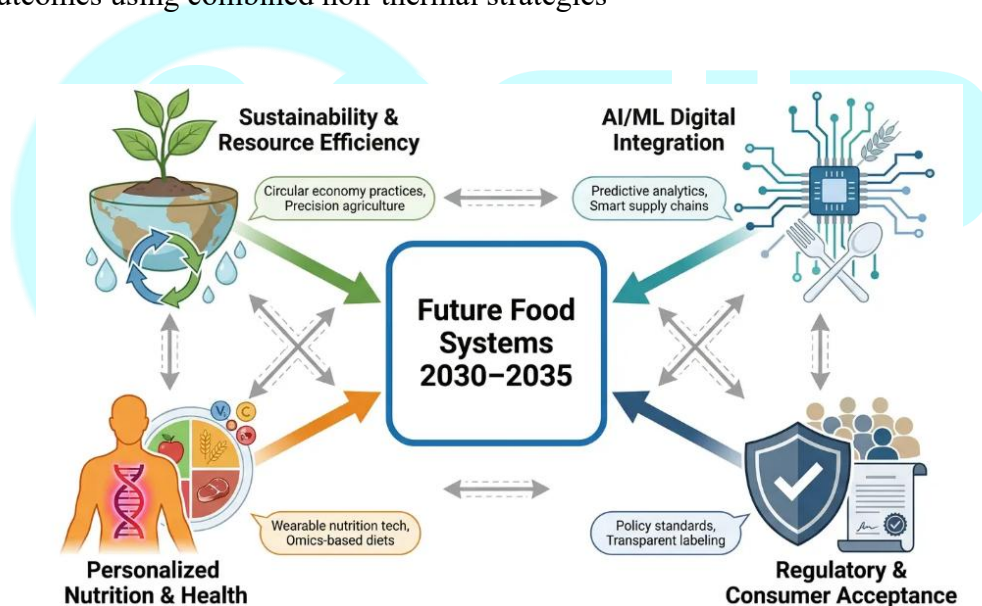


Figure 3. *Future prospects and research directions for AI-integrated non-thermal food processing. The diagram shows the convergence of sustainability goals, digital transformation, personalized nutrition, and regulatory frameworks in shaping the future of food processing technologies.*

6. Conclusion

Innovative non-thermal and advanced processing technologies, integrated with artificial intelligence and machine learning optimization strategies, represent transformative tools in food science and technology. They enable enhanced nutrient retention, microbial safety, and extended shelf life while maintaining quality and sensory attributes. The convergence

of non-thermal processing technologies with AI-driven optimization opens unprecedented opportunities for designing eco-efficient processes, minimizing resource use, and supporting resilient and sustainable food systems.

As consumer demand for minimally processed and nutritionally rich foods continues to rise, the implementation and optimization of these technologies will become increasingly critical. ML-based modelling can effectively predict process kinetics and optimize process parameters efficiently for ensuring better-quality products while handling complex, non-linear interactions between ingredients and processing conditions (Rashvand et al., 2025). The development of ML models, sensor integration, and intelligent systems is expected to yield non-thermal food processing methods with enhanced sustainability, safety, and quality.

Collectively, these innovations are paving the way toward safer, healthier, and more sustainable food systems, capable of meeting the challenges of future food security and nutrition demands. Moreover, the establishment of regulatory frameworks and the promotion of awareness efforts are essential to enhance consumer confidence. Investments in research, regulatory alignment, and industry adoption will drive their future success and impact on global food systems. The integration of AI-driven technologies with non-thermal processing represents a pathway to digital transformation in food manufacturing, contributing to climate-smart practices, resource efficiency, and the development of personalized nutrition solutions.

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