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Emerging Food Processing and Preservation Approaches for Nutrition and Health

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Authors' contributions

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ABSTRACT

This comprehensive review critically evaluates contemporary and emergent food processing and preservation technologies with a primary focus on enhancing nutrition and promoting health. The discourse delves into a spectrum of innovative methodologies, encompassing high pressure processing, pulsed electric field processing, oscillating magnetic field processing, nonthermal plasma, ultrasound processing, and avant-garde thermal technologies. A detailed analysis is provided, shedding light on the manifold impacts of these technologies on diverse facets such as food quality, sensory attributes, nutrient preservation, shelf-life augmentation, and the effective inactivation of pathogens. Furthermore, the document accentuates recent applications that exemplify the successful enhancement of nutritional profiles across a gamut of food products. The review not only scrutinizes the advantages but also delineates the challenges associated with the implementation of these cutting-edge technologies. An insightful exploration of potential future opportunities is incorporated, offering a forward-looking perspective on the evolving landscape of food processing and preservation. By expanding the discourse on these pivotal technologies, this review serves as a valuable resource for researchers, practitioners, and stakeholders interested in advancing nutrition and health outcomes through state-of-the-art food processing and preservation approaches.

Keywords: Food processing; nutrition; preservation technologies; emerging technologies; nutrient retention.

1. INTRODUCTION

Food processing is a crucial aspect of food production that transforms raw ingredients into consumable products. Traditional food processing methods have been practiced for centuries and involve techniques such as drying, fermenting, pickling, and cooking. While these methods have been effective in preserving food, they often come with limitations, particularly concerning the retention of essential nutrients and bioactive compounds. As consumer preferences shift towards healthier and more nutritious food options, there is a growing need for innovative food processing technologies that address these limitations [1,2].

Traditional food processing methods have played a vital role in making food safe for consumption and extending its shelf life. However, these methods can lead to the loss of important nutrients and bioactive compounds. For instance, heat processing, such as boiling and canning, may result in the degradation of heat-sensitive vitamins and antioxidants. Additionally, the use of excessive salt, sugar, and other preservatives in traditional processing can contribute to the development of unhealthy dietary patterns, including increased sodium and sugar intake.

Several emerging food processing technologies aim to overcome the limitations of traditional methods and better retain the nutritional value of foods.

1.1 Some Examples Include

1. **High-Pressure Processing (HPP):** This non-thermal processing technique uses high pressure to inactivate microorganisms while preserving the color, flavor, and nutritional content of foods.
2. **Pulsed Electric Field (PEF):** PEF involves the application of short electrical pulses to disrupt cell membranes, aiding in the extraction of nutrients and enhancing the overall nutritional profile of foods.
3. **Ultrasound Processing:** Ultrasound technology can be employed to improve the extraction of bioactive compounds, vitamins, and minerals from raw materials, leading to more nutrient-rich end products.

In addition to retaining nutrients, emerging processing technologies contribute to enhanced microbial safety and extended shelf life. These advancements help maintain the sensory qualities of foods, such as taste, texture, and color. Techniques like irradiation, cold plasma treatment, and advanced packaging methods can effectively control microbial contamination without compromising the sensory attributes of the final product [3].

The application of emerging processing technologies aligns with the growing consumer demand for healthier and more nutritious food options. By preserving the nutritional content of foods, these approaches support the development of products with enhanced health benefits. Manufacturers can now design foods that not only meet safety and shelf-life requirements but also contribute positively to consumers' overall well-being.

1.1.1 High pressure processing

High Pressure Processing (HPP) is a non-thermal food processing technology that utilizes elevated pressures to achieve microbial inactivation and extend the shelf life of various food products. The principle behind HPP involves subjecting food items to high pressures, typically between 100 and 1000 megapascals (MPa), which can inactivate spoilage microorganisms, pathogens, and enzymes without the need for high temperatures [4].

1.1.2 Principle and Mechanism of High Pressure Processing

HPP operates on the principle that high pressures can cause changes in the structure and functionality of microorganisms and enzymes, ultimately leading to their inactivation [5]. The mechanism involves the application of hydrostatic pressure uniformly throughout the food product, disrupting the cell membranes of microorganisms and altering the conformation of enzymes [6].

1.1.3 Effects on microbial inactivation, enzyme activity, protein structure, etc

1. **Microbial Inactivation:** High pressures applied during HPP can cause irreparable damage to the cellular structures of bacteria, yeasts, and molds, leading to microbial inactivation. This is particularly effective against foodborne pathogens, contributing to improved food safety.
2. **Enzyme Activity:** HPP can selectively inactivate enzymes responsible for food deterioration without the need for high temperatures. This is crucial for preserving the quality of the food, as enzymes that contribute to browning, texture changes, and flavor degradation can be inactivated.
3. **Protein Structure:** High pressures can induce changes in protein structures, affecting the functionality and texture of food products [7,8]. While some proteins may denature under pressure, HPP is generally considered mild enough to preserve the overall nutritional quality and sensorial attributes of proteins.

1.2 Influences on Nutritional Quality, Sensory Attributes, Shelf-Life

1. **Nutritional Quality:** One of the advantages of HPP is its minimal impact on the nutritional quality of foods. The process typically preserves the levels of heat-sensitive vitamins, antioxidants, and other bioactive compounds better than traditional thermal processing methods.
2. **Sensory Attributes:** HPP has minimal effects on the sensory attributes of foods, including taste, color, and texture. This is advantageous for maintaining the fresh-like quality of products, making it suitable for a wide range of food categories.
3. **Shelf-Life:** HPP extends the shelf life of foods by inactivating spoilage microorganisms and enzymes. This preservation method helps maintain the quality of the product for an extended period without the need for excessive use of additives or high temperatures.

1.3 Applications for Fruits, Vegetables, Meat, Seafood, Dairy, etc

1. **Fruits and Vegetables:** HPP is commonly used for fresh juices, purees, and minimally processed fruits and vegetables to maintain color, flavor, and nutritional content.
2. **Meat and Seafood:** HPP is applied to various meat and seafood products, such as deli meats, ready-to-eat meals, and seafood, to ensure microbial safety and preserve product quality.
3. **Dairy:** HPP is employed in the dairy industry for products like yogurt, cheese, and milk to extend shelf life and maintain nutritional quality without compromising sensory attributes.
4. **Ready-to-Eat Meals:** HPP is used for pre-packaged, ready-to-eat meals, as it helps preserve the quality and safety of the products without the need for excessive heat.

2. RESULTS

Several studies have demonstrated the efficacy of high pressure processing (HPP) for inactivating microorganisms while retaining nutrients in different food products. For example, Barba et al. [9] reported up to 5 log reductions in Listeria monocytogenes, Salmonella Enteritidis, Escherichia coli, and Staphylococcus aureus in meat and dairy products after high pressure treatment at 600 MPa. HPP was also found to better preserve vitamin C and antioxidant activity in strawberry and orange juice compared to thermal processing [10,11].

Table 1. Effects of high pressure processing on quality parameters in different food products

Food Product	Quality Parameter	Effects of High Pressure Processing
Fruits and Vegetables	Color and Flavor	Preserves natural color and flavor, maintaining freshness and visual appeal.
	Nutritional Content	Minimizes nutrient loss, especially heat-sensitive vitamins and antioxidants.
	Texture	Generally preserves the texture, preventing excessive softening or degradation.
Meat and Seafood	Microbial Safety	Effectively inactivates pathogens, extending shelf life and ensuring safety.
	Enzyme Activity	Suppresses enzymatic activity, preventing undesirable texture and flavor changes.
	Texture and Juiciness	Retains the natural texture and juiciness, enhancing overall eating experience.
Dairy Products	Microbial Safety	Enhances safety by reducing or eliminating harmful microorganisms.
	Texture and Creaminess	Preserves creamy texture and mouthfeel in products like yogurt and cheese.
	Shelf Life	Extends shelf life without compromising sensory attributes.
Ready-to-Eat Meals	Texture and Appearance	Maintains the original texture and appearance, ensuring consumer acceptance.
	Flavor	Preserves the natural flavor profile, avoiding the need for excessive additives.
	Shelf Life	Extends shelf life by controlling microbial growth and enzyme activity.

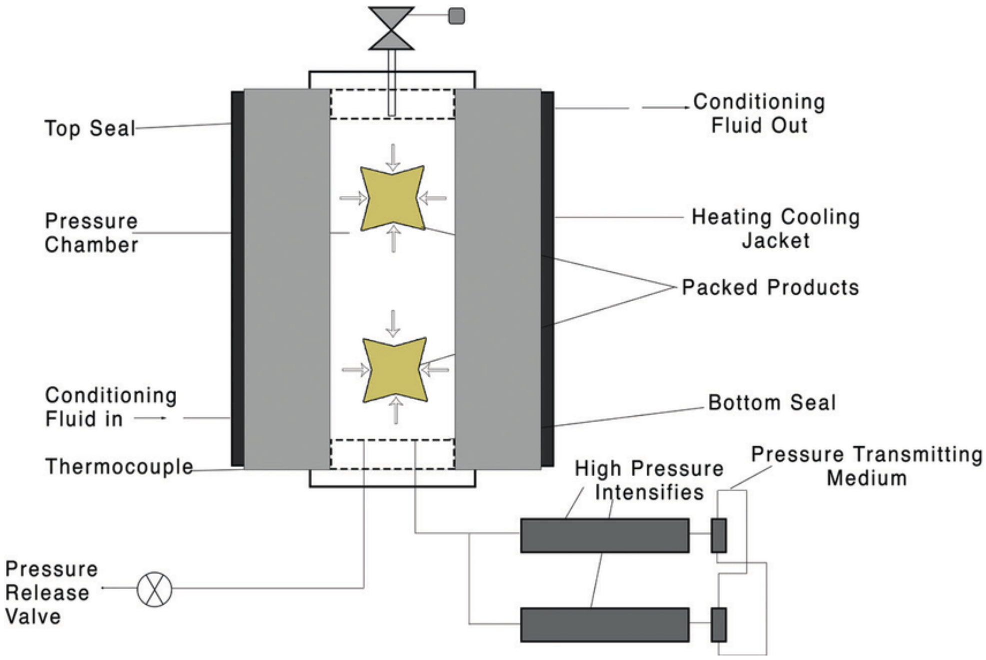

Fig. 1. Schematic diagram of a high pressure processing system

2.1 Pulsed Electric Field Processing (PEF)

Principle and Mechanism: Pulsed Electric Field Processing (PEF) is a non-thermal food processing technology that uses short pulses of electric fields to inactivate microorganisms, enzymes, and other spoilage agents in liquid foods. The process involves applying high-voltage electrical pulses to the food, creating pores in the cell membranes of microorganisms and disrupting cellular structures [12].

Effects on Microbial Inactivation and Enzyme Activity:

1. **Microbial Inactivation:** PEF effectively inactivates bacteria, yeasts, and molds by causing irreversible damage to their cell membranes. This enhances the microbial safety of liquid foods [13].
2. **Enzyme Activity:** PEF can disrupt enzymes responsible for the deterioration of food quality. By targeting specific enzymes, PEF helps control enzymatic activity, preserving the nutritional and sensory characteristics of the liquid food.

Influences on Nutritional and Sensory Parameters:

1. **Nutritional Parameters:** PEF generally has a mild impact on the nutritional quality of liquid foods. It minimizes the loss of heat-sensitive vitamins, antioxidants, and other bioactive compounds, preserving the overall nutritional profile [14].
2. **Sensory Parameters:** PEF has been shown to have minimal effects on the sensory attributes of liquid foods. It helps maintain the color, flavor, and texture of the products, providing a closer resemblance to fresh, untreated counterparts.

Applications for Juice, Milk, and Liquid Foods:

1. **Juice:**
- PEF is commonly applied in the juice industry to enhance microbial safety without the need for thermal pasteurization.
- It helps retain the fresh taste, color, and nutritional content of juices, meeting consumer preferences for minimally processed products.

2. **Milk:**
- PEF can be used in the dairy industry for processing milk and dairy beverages.
- It contributes to the inactivation of bacteria, extending the shelf life of milk products while maintaining their nutritional value.

3. **Liquid Foods:**
- PEF is applicable to a variety of liquid foods, including soups, sauces, and liquid-based products.
- It aids in preserving the quality and safety of these products, making them suitable for consumers seeking minimally processed and nutritious options.

Pulsed electric field (PEF) processing has shown promise as a non-thermal technique for fruit juice preservation. Bendicho et al. [14] reported that PEF treatment at 35 kV/cm for 1500 µs achieved a 5 log reduction in L. monocytogenes in orange juice while retaining higher vitamin C content compared to thermally treated samples [10,15]. PEF was also effective in reducing pectin methyl esterase and polyphenol oxidase activity in orange juice by 91.4% and 60.2% respectively, improving quality retention during storage [16].

2.2 Oscillating Magnetic Field Processing

Principle and Mechanism: Oscillating Magnetic Field Processing (OMFP) is a non-thermal food processing technology that utilizes the application of oscillating magnetic fields to achieve various effects on food products [17,18]. The principle involves exposing food items to alternating magnetic fields, leading to changes at the molecular and cellular levels.

Effects on Microbial Inactivation:

1. **Microbial Inactivation:** OMFP has the potential to inactivate microorganisms by disrupting their cellular structures through the application of oscillating magnetic fields. While not as commonly used as other technologies for microbial inactivation, research indicates its potential effectiveness in reducing microbial loads.

Impacts on Nutrient Retention and Sensory Attributes:

1. **Nutrient Retention:** OMFP aims to be a mild processing technique, and as such, it may have less impact on nutrient retention compared to traditional thermal methods.

The goal is to preserve the nutritional quality of foods by minimizing heat exposure.

2. **Sensory Attributes:** The impact on sensory attributes is likely to be less pronounced compared to thermal methods. OMFP is designed to minimize changes in flavor, texture, and color, contributing to the preservation of sensory qualities.

Potential Applications for Fruits, Vegetables, Liquids, and Semisolid Foods:

1. **Fruits and Vegetables:**
- OMFP may find applications in the processing of fruits and vegetables to extend shelf life, reduce microbial contamination, and preserve the nutritional content without the use of high temperatures [19,20].
- Potential applications include the treatment of fresh-cut produce and fruit juices.

2. **Liquids:**
- OMFP can be explored for liquid food products, such as juices and beverages, where the goal is to achieve microbial safety and maintain the fresh taste without significant heat-induced changes.

3. **Semisolid Foods:**
- Semisolid foods like sauces, purees, and baby foods may benefit from OMFP, especially if there is a desire to preserve the natural texture and sensory attributes while ensuring microbial safety.

4. **Diverse Food Categories:**
- OMFP could be applied to a variety of food categories to explore its potential in minimizing nutrient loss, preserving sensory qualities, and enhancing microbial safety without the use of high temperatures.

While the application of Oscillating Magnetic Field Processing is not as widespread as some other non-thermal processing technologies, ongoing research may uncover new possibilities and refine its efficacy in different food types. The focus on maintaining nutritional quality and sensory attributes makes OMFP an area of interest for the food industry seeking novel, minimally invasive processing techniques.

2.3 Nonthermal Plasma Technology

Fundamentals of Nonthermal Plasma Generation and Mechanisms: Nonthermal plasma refers to ionized gases that remain at or near room temperature. In the context of food processing, plasma is often generated using electrical discharges, creating a mix of reactive oxygen and nitrogen species, UV radiation, and electric fields [21]. The mechanisms involved include the generation of free radicals, UV radiation, and electric fields, which collectively contribute to various effects on microorganisms and food matrices [20].

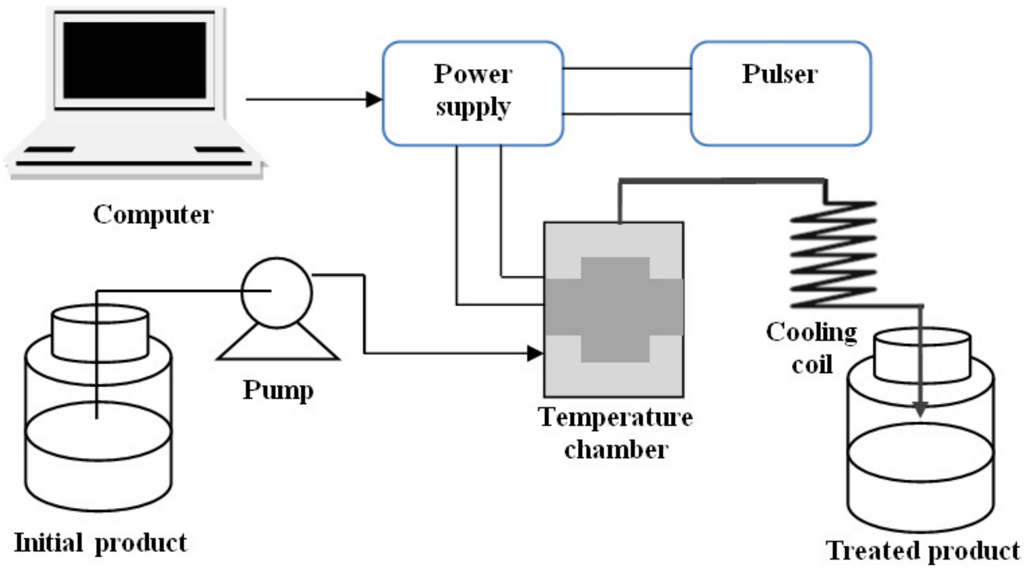

Fig. 2. Schematic representation of a pulsed electric field system

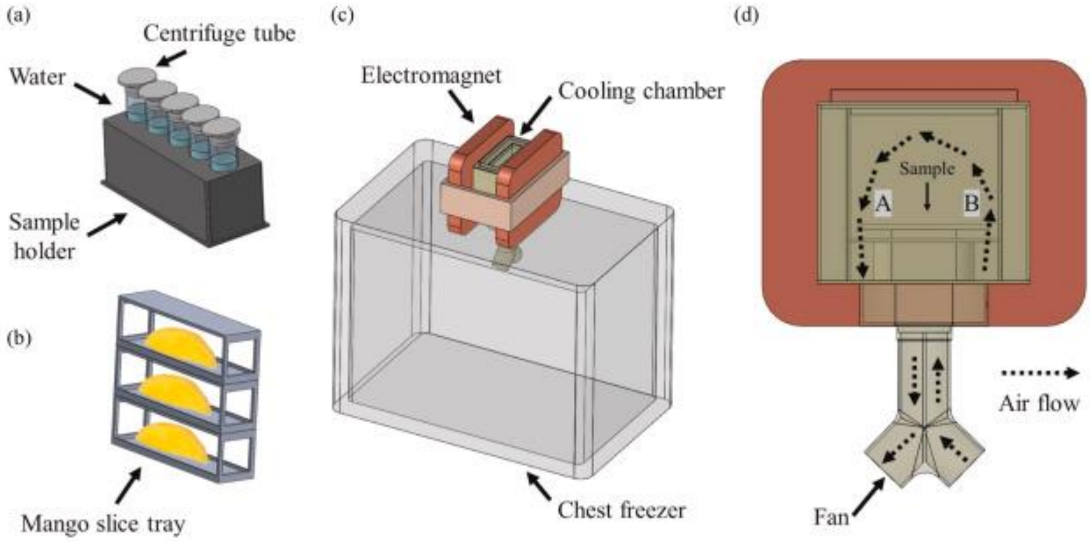

Fig. 3. Schematic diagram of an oscillating magnetic field processing apparatus

Influences on Microbial Destruction, Enzyme Inactivation, and Nutrient Retention:

1. **Microbial Destruction:**
- Nonthermal plasma effectively destroys microorganisms through the action of reactive species, including free radicals and UV radiation. Plasma disrupts cell membranes and DNA, leading to microbial inactivation [22,23].

2. **Enzyme Inactivation:**
- Enzyme inactivation occurs due to the impact of reactive species on the enzyme's structure. Nonthermal plasma can selectively target enzymes, helping to control undesirable enzymatic activities in food.

3. **Nutrient Retention:**
- Nonthermal plasma is designed to be a mild processing technology, and its short treatment times contribute to minimal nutrient loss [18]. The preservation of heat-sensitive vitamins and bioactive compounds is a key advantage.

Effects on Quality Parameters in Different Food Matrixes:

1. **Color, Flavor, and Texture:**
- Nonthermal plasma has shown to have minimal impact on the color, flavor, and texture of various food products, making it suitable for maintaining the sensory attributes in different matrices.

2. **Nutritional Quality:**
- As a non-thermal process, nonthermal plasma helps in retaining the nutritional quality of foods, ensuring that essential nutrients and bioactive compounds remain intact.

3. **Shelf Life:**
- Nonthermal plasma treatments contribute to extended shelf life by reducing microbial load and inactivating spoilage organisms, enhancing the overall preservation of food products.

Applications for Decontamination, Drying, Surface Modification, etc.:

1. **Decontamination:**
- Nonthermal plasma is extensively used for decontamination purposes, treating surfaces of fruits, vegetables, and various food packaging materials to reduce pathogens and spoilage microorganisms.

2. **Drying:**
- Plasma technology can be applied in drying processes to improve the efficiency of drying, reduce microbial contamination, and maintain the quality of the dried product.

3. **Surface Modification:**
- Nonthermal plasma treatments can modify the surface properties of materials, enhancing properties like wettability and adhesion, which can be useful in food packaging and processing.

4. **Polymer Crosslinking:**

- In the food industry, nonthermal plasma can be employed for polymer crosslinking, leading to enhanced mechanical and barrier properties in packaging materials.

5. **Food Safety:**

- Nonthermal plasma is applied for the decontamination of various food products, ensuring microbial safety without compromising the nutritional and sensory quality of the food.

Table 2. Applications of nonthermal plasma technology for food preservation and processing

Application	Description
Microbial Decontamination	Inactivates bacteria, molds, and viruses on the surfaces of foods.
Surface Decontamination	Applied to fruits, vegetables, and other food products to decontaminate surfaces without thermal damage.
Packaging Disinfection	Decontaminates food packaging materials, enhancing the overall safety of packaged products.
Enzyme Inactivation	Controls enzymatic activity in food, preserving quality and preventing undesired reactions.
Oxidation and Spoilage Prevention	Manages oxidation in foods, preventing spoilage and maintaining the quality of certain products.
Modification of Food Properties	Induces changes in physicochemical properties, including surface properties and texture.
Waste Reduction	Extends the shelf life of perishable products, reducing food waste and improving safety.
Seed and Grain Disinfection	Applied to seeds and grains to reduce microbial contamination, improving seed germination rates and safety.

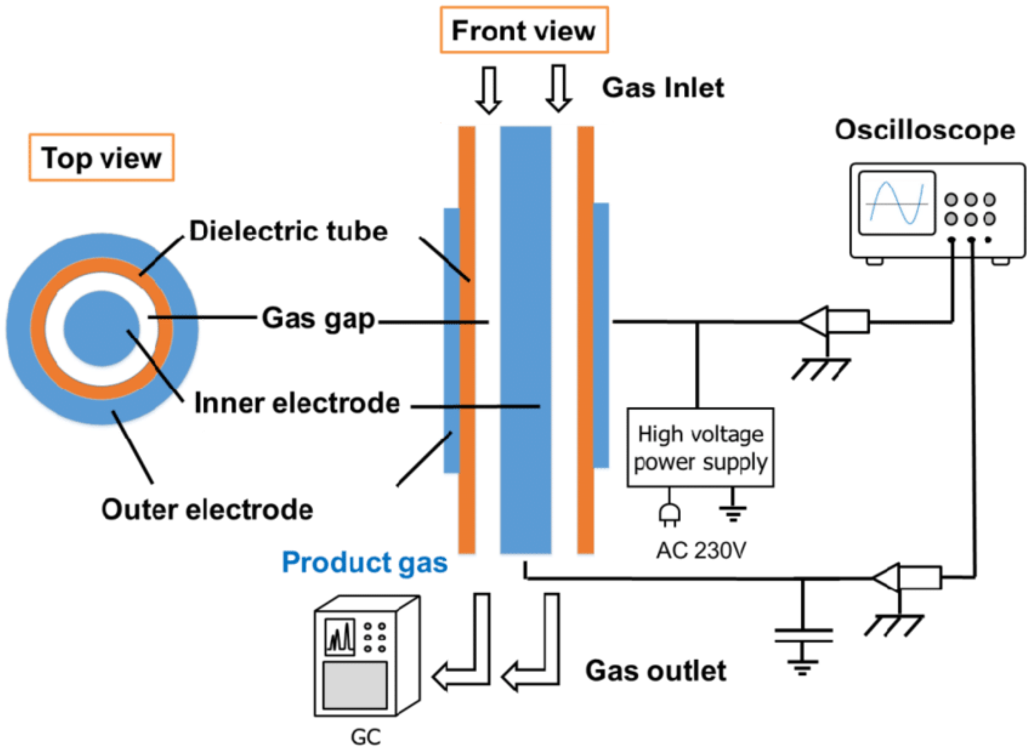

Fig. 4. Schematic representation of a dielectric barrier discharge plasma system

2.4 Ultrasound Processing

Principles of Power Ultrasound Technology: Power ultrasound involves the use of high-frequency sound waves (typically above 20 kHz) to induce mechanical vibrations in a liquid or solid medium [24,3]. This technology utilizes the effects of acoustic cavitation, where the formation, growth, and collapse of bubbles generate intense localized forces, leading to various physical and chemical effects [25,26].

Mechanisms of Microbial and Enzyme Inactivation:

1. **Microbial Inactivation:**
- Ultrasound disrupts microbial cell membranes through the phenomenon of cavitation, causing the formation and collapse of bubbles. The high shear forces and shock waves generated during cavitation contribute to microbial inactivation [27].

2. **Enzyme Inactivation:**
- Ultrasound-induced cavitation can disrupt the active sites and structures of enzymes, leading to their inactivation. The mechanical effects of ultrasound contribute to altering the conformation of enzymes.

Impacts on Nutritional and Sensory Qualities:

1. **Nutritional Quality:**
- Ultrasound is considered a mild processing technology that minimizes heat exposure. This helps in preserving the nutritional quality of foods, including the retention of heat-sensitive vitamins and bioactive compounds.

2. **Sensory Qualities:**
- Ultrasound generally has minimal impact on the sensory attributes of food. The short treatment times and low temperatures contribute to maintaining the original color, flavor, and texture of the products.

Applications for Emulsification, Extraction, Tenderization, etc.:

1. **Emulsification:**
- Ultrasound is used for emulsification purposes, where the mechanical effects of cavitation help in breaking down and dispersing fat globules in liquids. This is particularly useful in the production of stable emulsions [28,29].

2. **Extraction:**
- Ultrasound enhances the extraction of bioactive compounds from plant materials, such as polyphenols and essential oils. The cavitation process facilitates the release of intracellular components, improving extraction efficiency.

3. **Tenderization:**
- Ultrasound is applied in meat processing for tenderization. The mechanical effects of ultrasound disrupt the connective tissues, leading to improved meat tenderness.

4. **Cleaning and Disinfection:**
- Ultrasound is utilized for cleaning and disinfecting surfaces, equipment, and food contact materials in the food industry. The cavitation process helps in removing contaminants and reducing microbial loads.

5. **Dehydration:**
- Ultrasound-assisted drying is employed for dehydrating fruits and vegetables. The mechanical vibrations facilitate moisture removal, resulting in faster and more efficient drying processes.

6. **Dough Conditioning:**
- Ultrasound can be used for dough conditioning in baking processes. It improves the mixing and fermentation properties of dough, leading to enhanced bread quality.

7. **Homogenization:**
- Ultrasound contributes to the homogenization of various food products, ensuring uniform distribution of particles and improving product stability.

The application of power ultrasound has been demonstrated to improve microbial safety, extract bioactive compounds, and modify structural properties of foods. Guan et al. [27] showed that ultrasonic pretreatment of brown rice followed by drying resulted in 1.5 log and 1.7 log reductions in total plate count and total coliforms respectively compared to control. The cavitation effect of ultrasound also enhanced the extraction of anthocyanins from grape pomace by 60% compared to conventional methods [30-32].

Table 3. Effects of ultrasound processing on food quality attributes

Food Quality Attribute	Effects of Ultrasound Processing
Texture and Structure	- Softening or tenderization of meat products. - Modification of starch structure in cereals and grains.
Nutrient Retention	- Preservation of certain vitamins and antioxidants in fruits and vegetables.
Flavor Enhancement	- Improved flavor extraction in processes like brewing and extraction of aromatic compounds.
Shelf Life Extension	- Inhibition of microbial growth, contributing to the extension of shelf life in some products.
Mass Transfer	- Enhanced mass transfer during processes such as drying, brining, and marination, leading to more efficient food processing.
Enzyme Activation/Inactivation	- Activation or inactivation of enzymes depending on the frequency and intensity of ultrasound.
Emulsification and Homogenization	- Improved emulsification in the production of certain food products, leading to better stability and texture.
Deaeration	- Removal of dissolved gases, contributing to the prevention of oxidation and improved product stability.
Extraction Efficiency	- Enhanced extraction of bioactive compounds, flavors, and essential oils in the extraction processes.
Disinfection	- Inactivation of microorganisms, contributing to the microbial safety of certain food products.

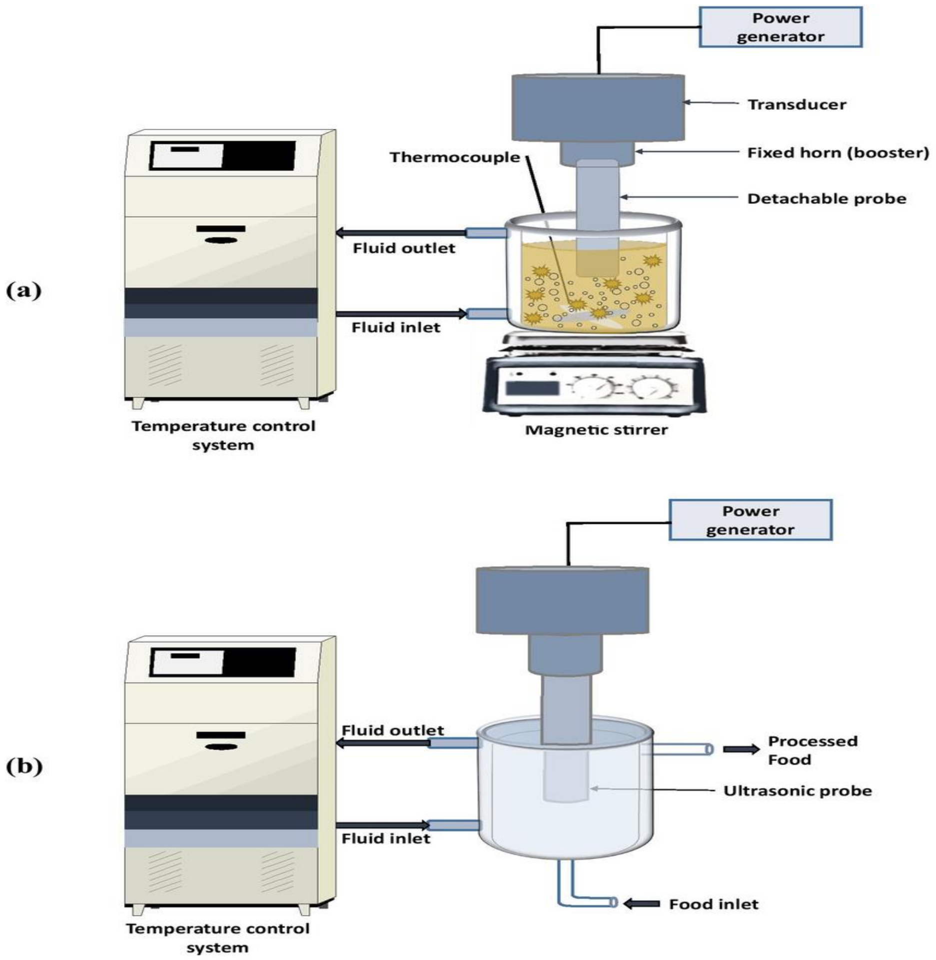

Fig. 5. Schematic diagram of an ultrasonic food processing system

2.5 Novel Thermal Technologies

Absolutely, emerging thermal pasteurization/ sterilization technologies like microwave-assisted thermal sterilization (MATS), radio frequency heating (RFH), infrared heating (IRH), ohmic heating (OH), and their combination with high-pressure processing (HPP) have shown promise in revolutionizing food processing [33]. These techniques offer improved nutrient retention and quality attributes, particularly beneficial for low-acid and acidified foods [34]. Here's an overview of these technologies:

1. **Microwave Assisted Thermal Sterilization (MATS):**

- MATS uses microwave energy to rapidly heat food, allowing for quick and uniform heating throughout the product [35]. It enables sterilization at lower temperatures and shorter times, preserving the quality attributes and nutrients of the food.

2. **Radio Frequency Heating (RFH):**

- RFH uses an alternating electrical current to generate heat within the food. It offers rapid and volumetric heating, ensuring effective pasteurization or sterilization while minimizing the impact on food quality and nutrient content [36].

3. **Infrared Heating (IRH):**

- IRH uses infrared radiation to heat the surface of the food directly. It provides rapid and controllable heating, making it suitable for surface pasteurization or sterilization without significantly affecting the food's interior quality.

4. **Ohmic Heating (OH):**

- OH passes an electric current through the food, causing it to heat up due to its electrical resistance [37,38]. This method enables uniform heating and is particularly effective for liquid foods. It helps retain nutrients and quality attributes due to shorter processing times [39].

5. **Combination with High-Pressure Processing (HPP):**

- Combining thermal technologies like MATS, RFH, IRH, or OH with HPP can synergistically enhance microbial inactivation while preserving food quality. HPP can reduce processing temperatures and times, further preserving nutrients and sensory characteristics [6,16].

6. **Improved Nutrient Retention and Quality Attributes:**

- These emerging thermal technologies focus on reducing processing temperatures and times, leading to better retention of heat-sensitive nutrients, flavors, and textures compared to traditional thermal processing methods.

7. **Applications for Low-Acid and Acidified Foods:**

- These technologies are particularly well-suited for low-acid and acidified foods, where traditional thermal processing might compromise the quality and nutritional content due to higher temperatures and longer processing times.

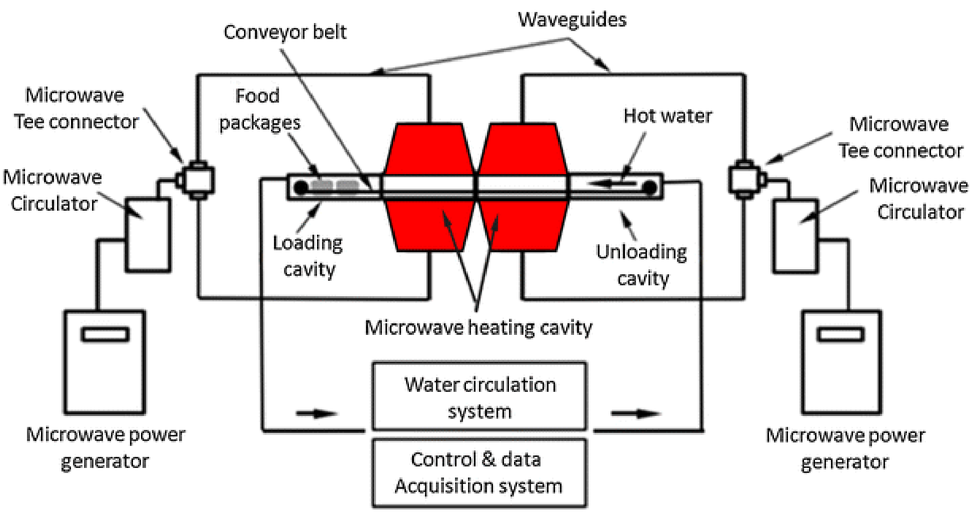

Fig. 6. Chematic representation of a continuous microwave assisted thermal sterilization system

By employing these emerging thermal technologies and combinations thereof, the food industry aims to meet consumer demands for minimally processed foods while ensuring safety and extending shelf life without compromising nutritional value and quality attributes.

Cold plasma technology is emerging as an effective non-thermal approach for microbial decontamination and enzyme inactivation. Studies by Baier et al. [4] showed that cold plasma achieved up to 5 log reductions in E. coli and L. monocytogenes populations on lettuce, cucumber, and strawberries after 5 minutes of exposure. Misra et al. [17] also demonstrated that in-package cold plasma treatment inactivated up to 99% of polyphenol oxidase and peroxidase enzymes in mango pulp, minimizing browning during storage [40-50].

3. FUTURE OPPORTUNITIES AND CHALLENGES

As the food industry explores novel processing approaches for enhanced nutrition and quality, several opportunities and challenges arise. Here are some key considerations:

1. **Optimizing Processing Parameters:**
- *Opportunity:* Fine-tuning processing parameters (e.g., temperature, pressure, duration) can lead to improved nutrient retention and product quality.
- *Challenge:* Identifying the optimal conditions requires extensive research and may vary based on the type of food, making it a complex task.

2. **Comprehensive Studies on Nutrient Bioavailability:**
- *Opportunity:* In-depth studies on nutrient bioavailability can provide insights into how novel processing methods affect the absorption and utilization of nutrients in the human body.
- *Challenge:* Conducting comprehensive studies requires interdisciplinary collaboration and a deep understanding of nutritional science, food chemistry, and human physiology.

3. **Technical and Economic Feasibility:**
- *Opportunity:* Developing cost-effective processes is crucial for the widespread adoption of novel technologies.
- *Challenge:* Balancing technical advancements with economic feasibility can be challenging, as sophisticated technologies may initially be expensive to implement.

4. **Consumer Acceptance of Novel Processed Products:**
- *Opportunity:* Educating consumers about the benefits of novel processing methods and their positive impact on nutrition and quality.
- *Challenge:* Overcoming consumer skepticism and preferences for traditional processing methods, as well as potential concerns about the safety and taste of novel products.

5. **Regulatory Issues and Approval:**
- *Opportunity:* Collaborating with regulatory bodies to establish clear guidelines and standards for novel preservation approaches.
- *Challenge:* Navigating the regulatory landscape and obtaining approvals for new technologies, which can be a lengthy and complex process.

6. **Sustainability Considerations:**
- *Opportunity:* Incorporating sustainable practices in novel processing methods to align with growing consumer demand for eco-friendly products.
- *Challenge:* Balancing sustainability with the need for efficient and effective preservation methods, considering the environmental impact of both processes and packaging.

7. **Global Market Adoption:**
- *Opportunity:* Expanding the use of novel processing technologies in diverse global markets to address different food safety and nutritional challenges.
- *Challenge:* Adapting technologies to meet specific regional needs and overcoming infrastructure limitations in certain areas.

8. **Integration of Digital Technologies:**
- *Opportunity:* Leveraging digital technologies for process monitoring, control, and optimization.
- *Challenge:* Integrating digital solutions may require investments in technology infrastructure and skilled personnel.

9. **Public Awareness and Education:**
- *Opportunity:* Building public awareness about the benefits of novel processing

methods and their role in enhancing food safety and nutritional value.

- *Challenge:* Developing effective communication strategies to convey complex scientific information to the general public.

4. CONCLUSION

The advancements in emerging processing technologies hold great promise for the food industry. The ability to create healthier, higher quality foods while addressing current challenges presents an exciting opportunity. Future research and collaborative efforts are necessary to unlock the full potential of these technologies, ensuring their successful integration into the global food supply chain and contributing to improved public health through dietary choices.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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