Roles of some Innovative Non-Thermal Processing Techniques on Food Quality and Safety

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ABSTRACT

New food processing methodologies have emerged in response to consumers' increasing demand for food products that are not only safe, delicious and minimally processed but also possess an extended shelf-life with consistent quality. The evolving lifestyle trends, characterized by a heightened interest in nutritionally-rich foods, bioactive compounds and overall sensory quality, have presented significant challenges to the food processing industry, driving the need for the development of novel and innovative food processing techniques. Conventional methods like pasteurization and commercial sterilization have long been used in the food industry for their efficacy in preserving foods through the eradication of harmful microorganisms and enzymes. However, the elevated temperatures generated by these methods can often lead to detrimental effects on food constituents, resulting in compromised organoleptic quality and diminished nutritional value. Hence, the need for novel non-thermal food processing techniques which can safeguard the overall quality attribute of food products with an extended shelf-life while ensuring total food safety becomes necessary. These innovative techniques include high-pressure processing, pulsed electric field, cold plasma treatment, ultrasound and hydrodynamic cavitation stand out among others, thus, exerting considerable influence on consumer health and representing major advancements in food processing. This review intends to furnish essential insights into various novel non-thermal food processing techniques, elucidating their preservative mechanisms, efficacy and suitability across diverse food categories and their impact on the food safety.

INTRODUCTION

Recent advancements in food processing techniques have been driven by consumer preferences for health-promoting foods rich in nutritional and nutraceutical values (Hameed *et al*., 2018). While the traditional focus of food processing methods was primarily on ensuring food safety and extending shelf life, contemporary consumer expectations have evolved. The production of safer food alone is no longer sufficient; therefore, consumers now seek products with substantial nutritional attributes, bioactive compounds and appealing sensory properties (Knoerzer *et al*., 2016). The attributes of food, including taste, texture, appearance and nutritional value, are significantly influenced by the processing methods employed (Knoerzer *et al*., 2016). Meanwhile, microorganisms, being the primary agents of food spoilage and contamination, are targeted by various food preservation techniques. The approaches employed by the food industry typically involve either microbial inactivation or the inhibition of microbial growth. Besides, conventional heat-based methods of reducing harmful microorganisms such as mild heat treatment, pasteurization, and in-container sterilization can negatively impact taste, nutritional content and appearance (Knoerzer *et al*., 2016). In contrast, the emergence of innovative non-thermal processing technologies has led to innovative processing techniques that prioritize improved quality and safety. The adoption of these non-thermal treatments is driven by several factors such as their milder processing conditions and environmental friendliness. These methods reduce reliance on solvents and organic chemicals, thus, contributing to a more sustainable approach to food processing (Basak and Annapure, 2022). With consumers increasingly demanding natural, nutrient-rich food products devoid of preservatives and additives, there has been a swift rise in the development of innovative non-thermal technologies to meet these preferences (Knorr *et al*., 2011).

Non-thermal or minimal processing techniques offer the advantage of preserving foods without subjecting them to significant heating, thus preserving their nutritional integrity and sensory attributes. These novel technologies have the potential to extend the freshness of foods while retaining their natural flavours and colours. Such technology results in products of improved quality and consumer appeal. Consequently, these techniques have gained significant attention from food manufacturers seeking novel processing methods (Brennan and Grandison, 2012). The advent of such innovative technologies strikes a delicate balance between safety and minimal processing, addressing both economic constraints and the demand for superior quality (Tokusoglu, 2015).

Moreover, these advancements contribute to environmental sustainability by minimising power and water consumption, consequently lowering the carbon and water footprint associated with food processing. In this way, innovative technologies play a vital role in fostering both environmental stewardship and food security (Knoerzer *et al*., 2015).Gao *et al*. (2016) reported that food components responsible for colour, flavour and taste are particularly sensitive to heat, making thermal processing prone to altering the quality of commercial food items and impacting their overall acceptability. As a result, there has been a quest for alternative methods to thermal food processing that can produce safer products with enhanced quality, nutritional content, and sensory properties. Thus, motivating food experts to delve into alternative inactivation techniques. The novel processing techniques include high-pressure processing, ultrasound extraction, pulsed electric fields, cold plasma and hydrodynamic cavitation which offer promising avenues for food processing that mitigate the detrimental effects associated with thermal methods while maintaining and enhancing product quality and nutritional value.

INNOVATIVE NON-THERMAL FOOD PROCESSING TECHNIQUES

High-pressure processing technology

High-pressure processing (HPP) emerges as a promising non-thermal preservation method, offering an effective substitute to traditional food preservation techniques for enhancing the safety and shelf life of perishable foods (Balasubramaniam and Farkas, 2008). This technique is characterized by non-thermal pasteurization which subjects products to pressures typically ranging between 300–600 MPa for durations of about 10 minutes. Notably, HPP boasts several advantages over traditional thermal processing methods, including abbreviated process times, which minimize heat-induced damage, and the preservation of product attributes such as flavour, texture, colour, and vitamins (Hameed *et al*., 2018). The HPP technology demonstrates efficacy in inactivating pathogenic and spoilage microorganisms (bacteria, yeast, mould and viruses), its effectiveness against bacterial spores and enzymes is limited (Marszałek *et al*., 2017). Various factors such as microbial species, food composition, pH and water activity, influence the efficiency of microbial inactivation by HPP (Zhang *et al*., 2017). This technique finds application in the processing of numerous liquid and semi-solid foods as well as fruit juices, jellies, purees and smoothies (Nayak *et al*., 2017). Nevertheless, the current adoption of HPP is impeded by high capital investment requirements and limited throughput (Chang *et al*., 2017).

Pulsed electric field technology

Puled electric field technique (PEF) involves subjecting the food to a pulsed high-voltage field for less than 1 second, serving as a method of food preservation. This is famous for its capacity to neutralise bacteria in liquid-based food items at reduced temperatures. Comparative studies indicate that PEF processing offers superior retention and strong ability of biologically active compounds such as phenolic compounds, carotenoids and flavonoids to remain stable during storage when compared to thermal processing. It finds industrial applicability in certain liquid products, particularly functional foods, nutraceutical products and juices, while closely resemble freshly squeezed products, particularly regarding aroma profile (Morata *et al*., 2017).The PEF technology shows promise as an alternative to thermal techniques in the pasteurization and sterilization of liquid foods. This can be attributed to its ability to maintain the nutritional value, sensory characteristics, safety and overall products' quality at lower operational costs. To enhance efficacy, PEF can be combined with additional processes such as mild thermal treatment or pH and water activity control (Khouryieh 2021). Studies suggest that integrating PEF treatment with moderate temperatures and an antimicrobial agent is effective against both gram-positive and gram-negative pathogenic bacteria can significantly improve process efficiency, reduce the number of pulses, and outlet temperature, and lead to substantial energy cost savings (Aruda *et al*., 2021).

The efficacy of PEF in microbial inactivation depends on various factors including the intensity of the electric field, number of pulses, pulse duration, pulse waveform, and temperature (with 50 – 60°C resulting in increased microbial inactivation), as well as the conductivity of the product. However, foods with high conductivity (salt content), as well as liquid products containing particulates, are considered unsuitable for PEF treatment. Additionally, the lifecycle stage of the target microorganisms also influences PEF lethality, with rapidly growing and dividing populations being the most susceptible, while those in stationary or lag phases exhibit some resistance (Dukić-Vuković *et al*., 2017). PEF technology has demonstrated successful application in the pasteurization of fluid foods like juices, milk, yoghurt, soups, and liquid eggs. However, PEF use is limited to food products without air pockets and having minimal electrical conductivity. Ensuring proper treatment requires that the largest particle size in the liquid be smaller than the gap of the treatment region in the PEF chamber (Hameed *et al*., 2018).

Cold plasma technology

Cold plasma (CP) is classified as another state of matter distinct from solids, liquids and gases which can exist in either thermal or non-thermal forms according to the conditions in which it is produced. As a non-thermal treatment, it has the potential for protein modification and has already been recognized as an innovative method for altering the content of carbohydrates, lipids and proteins in food (Jadhav and Annapure, 2021; Basak and Annapure, 2022). While thermal plasmas require significant power, such as high temperature and pressure conditions, non-thermal plasmas utilize considerably less power, often generated by electric or magnetic discharges and obtained at lower pressures, thereby attracting significant industrial interest. Although relatively underexplored, CP has been utilised in sanitizing the surfaces of fresh fruits and vegetables, liquid products (juices), food equipment surfaces (Misra and Roopesh, 2019). Recognized as a sustainable method, CP has been identified for its environmentally friendly approach to improving seed germination, decontaminating food-contact surfaces, modifying food ingredients, and inactivating enzymes (Bourke *et al*., 2018). Additionally, CP requires minimal use of solvents and chemicals, and leaves no residue, therefore, ensuring a clean label for the treated food or ingredient (Misra and Roopesh, 2019).

Cold plasma technology emerges as an effective alternative to thermally based microbial inactivation methods, exhibiting comparable microbial inactivation properties against major pathogens while exerting minimal or no effect on the nutritional or other quality aspects of the product. However, the potency of CP processing can be influenced by cell density, with upper cell layers serving as physical barriers to underlying cells, particularly in complex bacterial multilayer structures like biofilms, hence, impacting the practical application of the technique in the food sector (Misra *et al*., 2014). Its suitability for treating heat-sensitive food products stems from the fact that ions and uncharged molecules gain minimal energy, thereby, remaining at low temperatures (Pankaj *et al*., 2018).The rising demand for improved food safety and quality, while maintaining nutritional and sensory attributes, has sparked greater attention towards innovative low-temperature food processing methods. These emerging technologies primarily rely on physical processes utilizing ambient or moderately elevated temperatures and short treatment times to inactivate microorganisms. The efficacy of these processes is largely influenced by the properties of the food matrix, applying a universal approach to their application may be challenging. Further research is warranted to establish and expand the industrial applications of these technologies, overcoming potential barriers such as high capital costs that could impede industrial adoption (Komitopoulou 2024).

Ultrasound technology

Ultrasound (US) emerges as a promising, sustainable and cost-effective alternative to traditional food processing methods. This approach offers numerous advantages by enhancing food quality, preserving food, reducing processing time and facilitating process monitoring (Arruda *et al*., 2021). As a non-thermal technology, its main objective is to prolong the shelf life of food products while minimizing temperature to preserve nutritional characteristics such as texture, colour, taste and aroma, similar to fresh food (Zhang *et al*., 2018).

Ultrasound technology is recognized as a green food processing technique with the potential to enhance mass and energy transfer processes, making it one of the technologies that enables food processing with lower energy and water consumption, thereby promoting more sustainable and environmentally friendly processing methods (Chemat *et al*., 2017). In the food industry, high-powered ultrasound applications operate within the range of 20-100 kHz, particularly in systems where a liquid or gaseous medium (such as air) is used to propagate ultrasound waves (Bermudez-Aguirre *et al*., 2011). However, the scope of ultrasound applications extends beyond this, encompassing cleaning, atomization, homogenization and emulsification, defoaming, drying and freezing (Astráin-Redín *et al*., 2021).

Recent research has focused on ultrasound's potential to enhance the nutritional value and organoleptic qualities of food (Charoux *et al*., 2017). This technology facilitates mass and energy transfer processes, enabling the formation of infusions at lower temperatures (around 30 ^{0}C) with higher total polyphenol, carotenoid, and anthocyanin contents (Ciudad-Hidalgo *et al*., 2020). Moreso, US assists in the elimination of naturally occurring compounds in foods that may be harmful to human health, such as oligosaccharides from pulses or heavy metals from edible crabs (Antunes-Rohling *et al*., 2018). During dehydration, US minimizes the loss of bioactive constituents and improves the appearance of dehydrated products (Charoux *et al*., 2017).Furthermore, US facilitates the extraction of functional compounds from foods (pectins, gums, cellulose, alginates and carrageenans) which influence structure, stability and viscosity to food products (Singh *et al*., 2020; Laurora *et al*., 2021). It also enhances the extraction of protein, which can be used to enrich foods with low protein content or serve as functional additives like foam or emulsion stabilizers (Jain and Anal, 2016; Lafarga *et al*., 2018).

Hydrodynamic cavitation technology

Hydrodynamic cavitation (HC) involves the formation, expansion and abrupt collapse of bubbles, generating high pressures ranging from 100– 5000 bar and temperatures between 727 – 9727^{0}C for mere fraction of seconds. According to Gogate (2011), HC represents an innovative and underexplored non-thermal technology in food processing. It appears more physically effective and energy-efficient compared to ultrasound treatment. This technology holds promise in non-thermal food processing by potentially eliminating microorganisms, reducing enzyme activity and preserving essential nutritional and physicochemical properties (Shalini *et al*., 2023).The HC technology serves various purposes, including creating stable emulsions, homogenizing food constituents and extracting food components like polyphenols, essential oils, and pigments (Shalini *et al*., 2023). Furthermore, HC finds utility in water treatment, biodiesel, and biogas production (Shalini *et al*., 2023). This phenomenon can be induced either by mechanically rotating an object through a liquid or by fluid passage through a constriction, leading to increased velocity at the expense of local pressure (Huang *et al*., 2013). The constriction creates massive gas bubbles that collapse violently downstream, generating potent mechanical waves and high-speed micro-jets (Kuldeep *et al*., 2016). The collapse of cavities produces highly reactive hydroxyl radicals, which can be harnessed for various applications.

This novel technology is recognized as a clean and advantageous technology platform, characterized by the absence of additional chemicals, compactness, inline reactors, and low costs. In the food industry, HC is pivotal in extraction, processing, and sterilization. Various high-acid fluid foods, such as tomato juice, apple juice, and skim milk, have been processed in HC reactors for commercial sterility (Hammed *et al*., 2018). Research indicates that HC generates adequate destructive forces to deactivate bacteria, yeast cells and heat-resistant bacterial spores. The main advantage lies in its ability to achieve lower operating temperatures for sterilization, enabling the safe processing of acidic fruit juices, salad dressings, and milk at reduced temperatures, thereby preserving superior product quality. Employing hydrodynamic cavitation as a processing technology allows for minimal heat treatment of fluid foods while extending shelf life, retaining heat-labile nutrients and flavour components which results in superior products that align with consumption trends (Hameed *et al*., 2018).

CONCLUSION

The emergence of novel non-thermal food processing technologies characterized by improved quality and safety has led to significant innovations in processing techniques. The consumer preferences, research and development efforts have also led to the development of novel techniques such as high-pressure processing, pulsed electric field, ultrasound, cold plasma and hydrodynamic cavitation, which represent cutting-edge advancements in food processing. These innovative technologies have played a pivotal role in enhancing the bioactivity of functional components, food quality and safety. Their increasing applicability is driven by their significant health impacts, leading to a reduction in consumer complaints. It is anticipated that soon, traditional thermal processing methods will be largely replaced by innovative food processing techniques. Consequently, there is a concerted effort to develop more environmentally sustainable production systems to ensure the production of safe and high-quality food products.

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