

Recent advances in nonthermal hurdle approach in the food sector

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Abstract

Nonthermal hurdle technologies have emerged as promising alternatives to conventional thermal processing in the food industry. These technologies utilize multiple barriers, such as ultrasound, high hydrostatic pressure, pulsed electric fields, and other techniques, to ensure microbial safety, extend shelf life, and preserve the nutritional and sensory qualities of foods. This review delves into the principles, applications, and synergistic effects of nonthermal hurdles in food preservation, highlighting their broader implications for the food industry. It explores how these technologies address the limitations of traditional thermal methods, such as nutrient loss and flavor degradation, while meeting stringent safety and quality standards. Additionally, the review outlines the most commonly utilized combinations of nonthermal hurdles, offering insights into their practical applications and effectiveness. These advancements present significant opportunities to reduce the reliance on chemical additives and promote sustainability in food production. By reducing energy consumption and minimizing waste, nonthermal technologies contribute to SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). Furthermore, their role in improving food safety and accessibility aligns with SDG 2 (Zero Hunger), while promoting healthier food options supports SDG 3 (Good Health and Well-Being). Continued research and development are essential to optimizing these technologies for broader applications across diverse food types and improving their efficacy in ensuring food safety and quality. Extensive research has demonstrated significant advancements in the application of nonthermal hurdle combinations within the food sector. Ongoing studies are actively exploring diverse combinations to enhance food quality. The adoption of these nonthermal hurdle technologies holds immense potential for the food industry, promising greater efficiency and improved food quality standards.

Keywords: food preservation; hurdle; nonthermal technology; microbial inactivation; recent advances

Highlights

- Nonthermal technologies mitigate the risk of food overheating inherent in traditional processing methods.
- Hurdle combinations of nonthermal techniques enhance nutrition retention, meeting consumer demand for healthier food options.
- These combinations reduce processing time while improving preservation efficacy.

- Nonthermal hurdles represent an innovative pathway for the food processing sector, offering effective and sustainable processing methods.

Introduction

Recent shifts in consumer preferences reflect a growing inclination towards healthier lifestyles, emphasizing the

consumption of natural and fresh foods free from chemical additives (Mehraj *et al.*, 2023; Anand *et al.*, 2022; Zhang *et al.*, 2018). This trend is driven not only by evolving lifestyles and technological advancements but also by higher standards and expectations among consumers (Chakka, Sriraksha, and Ravishankar, 2021; Jadhav, Annapure, and Deshmukh, 2021). As the environment and population continue to grow, there is an increasing demand for enhanced food processing techniques. The traditional method of processing food is through thermal treatments, a practice that has been in place for centuries. Over time, numerous advancements have been made in this area (Chakka, Sriraksha, and Ravishankar, 2021). The most commonly used thermal treatments include baking, frying, drying, pasteurization, sterilization, and ultra-high temperature treatments (Mehraj *et al.*, 2023). Treating food with these thermal technologies causes nutritional and quality losses, even though they improve the shelf life of the food material (Mehraj *et al.*, 2023; Jadhav, Annapure, and Deshmukh, 2021). The use of thermal methods in food preparation also leads to the production of harmful chemical toxicants, such as furan, amines, acrylamide, and polycyclic hydrocarbons (Rathod, Nikheel *et al.*, 2022). Moreover, some of these thermal processing techniques consume a lot of energy (Bigi *et al.*, 2023). Destroying microorganisms in food necessitates the use of high temperatures, which unfortunately results in the loss of heat-sensitive nutrients. To achieve both the destruction of harmful microbes and the retention of quality and nutritional parameters in food, the need for improved technologies and methodologies is vital. By embracing nonthermal technologies, the aforementioned issues are resolved as they are integrated into the regular processing line (Jadhav, Annapure, and Deshmukh, 2021).

Nonthermal food processing techniques do not raise the temperature of food as traditional thermal methods do. They effectively reduce microorganisms, extend shelf life, and enhance texture and sensory qualities through brief treatment periods. Maintaining low temperatures preserves nutritional value, including heat-sensitive vitamins and proteins. These methods also improve food quality by eliminating food-degrading microorganisms while retaining sensory characteristics (Mehraj *et al.*, 2023; Anand *et al.*, 2022). Certain food-degrading enzymes are also destroyed during treatment. Nonthermal technologies like pulsed electric field, ultrasound, cold plasma, pulsed light, high-pressure processing, UV light, moderate electric field, and irradiation, including X-rays, gamma rays, and electron beams, have been widely used in food processing industries (Mehraj *et al.*, 2023; Jayasena *et al.*, 2023). Among these, an evolving technology called a moderated electric field (MEF) has the potential to improve food production in an environmentally friendly manner (Alsaedi *et al.*, 2023). Parallel

to ohmic heating, MEF applies alternating current without producing heat because of a regulated electrical field intensity. Non-thermal sterilization, or decontamination at low temperatures, is a promising application for MEF (Al-Hilphy, Abdulstar, and Gavahian, 2021; Alsaedi *et al.*, 2024). Irradiation in food is an emerging technique that uses ionizing irradiation emitted by radioactive isotopes to react with products to produce chemical, physical, and biological effects. Researchers favor electron beam (EB) over X-ray food treatment due to its non-radioactive source, high-energy electrons, which efficiently sterilize food without compromising quality, addressing consumer concerns about radioisotopes in food. Irradiation using an electron beam is regarded as novel in comparison to other non-thermal methods and is yet to be explored widely (Wei, Mei, and Xie, 2022). To minimize nutrient loss and enhance the quality of processed foods, nonthermal technologies play a pivotal role. They advance food processing by integrating multiple technologies, thereby pushing the boundaries of quality improvement (Anand *et al.*, 2022).

An advancement in food preservation is the application of hurdle technologies, which combine several methods to maximize the overall result (Khezerlou *et al.*, 2023). The combination of multiple technologies is termed hurdle technology. In summary, the hurdle technique is the purposeful and astute application of a variety of current and cutting-edge preservative methods. It creates a sequence of preservative elements that any microbe present should be unable to overcome. Reducing the severity of any one treatment method to maintain food quality is the main goal of hurdle technology (Obileke *et al.*, 2022). In order to accomplish multi-target, moderate, but dependable preservation effects, the hurdle concept is an efficient strategy that promotes the clever combination of various preservation techniques (Aaliya *et al.*, 2021). When using hurdles, product groupings should be considered carefully based on shelf life, growth conditions, and initial microbial load. Each hurdle can affect color, texture, or nutrient content. Combining multiple barriers is crucial when one alone cannot halt spoilage or pathogens. Hurdle technology extends beyond homeostasis disruption to address specific preservation factors for different organisms (Mahmoud *et al.*, 2022). While both new thermal and nonthermal methods show promise individually, combining multiple emerging thermal treatments, nonthermal techniques, and thermal-nonthermal strategies industrially has shown greater efficacy (Rifna *et al.*, 2019; Kulawik *et al.*, 2022; Aaliya *et al.*, 2021). When synergistically combined with other hurdle approaches, they can effectively replace chemical preservatives in food, a highly desirable outcome for most consumers (Roobab *et al.*, 2022). This review provides an in-depth discussion of nonthermal hurdle technologies. Numerous nonthermal technologies have already been

employed in combination to enhance processing effectiveness, as depicted in Figure 1. Ongoing research continues to explore and advance these approaches. Initially, this technology was used as a pre-treatment to improve the process, followed by another nonthermal technology that imparts better treatment and utilization of food. By removing the constraints associated with individual technologies, the hurdle framework increases the effectiveness and scope of applications while reducing the negative effects on food quality (Bigi *et al.*, 2023). This paper investigates the effectiveness of various nonthermal technologies used as hurdles in food processing for a range of applications, including preservation. It further evaluates their impact on nutritional content and explores their broader implications for the food industry. Additionally, the paper examines the most commonly employed or frequently utilized combinations of nonthermal hurdles, providing an overview of their practical applications and performance.

Why a Nonthermal as a Hurdle?

Originally, the primary objective of the food processing sector was to preserve food and extend its shelf life for continuous availability. However, the focus has since evolved beyond mere preservation from microbial spoilage to include consideration of additional parameters, such as nutritional aspects (Patel and Patel, 2023). Conventional thermal processing methods typically

result in the denaturation of protein, the loss of nutritional value, and ineffective fruit and vegetable preservation. In addition, the use of chemical additives can lead to environmental issues or even turn them into carcinogens (Obileke *et al.*, 2022).

Consumers expect that food consumed not only meets safety standards but also contributes positively to health and serves as a source of energy (Jadhav, Annapure, and Deshmukh, 2021). Initially, awareness of the nutritional content of processed foods was limited, as homemade meals were generally preferred for their perceived health benefits. However, with modernization came a shift towards convenience, driving increased consumption of processed foods. Moreover, the year-round availability of ingredients has bolstered the appeal of processing technologies. A good food processing procedure is one that produces little to no impact on the final product's texture, color, flavor, or nutritional value while using minimal resources and little processing time (Patel and Patel, 2023). This provides a better understanding of nonthermal technologies, which have multiple effects, such as preservation, prolonging the shelf life of food, and retaining the nutritional parameters in processed food products. Food materials' properties are altered using nonthermal techniques to offer them the required sensory attributes after processing (Chen *et al.*, 2022). Foods treated with this technique have mild to no loss in nutritional content (Kulawik *et al.*, 2022). The hurdle application of these technologies further reduces process time.

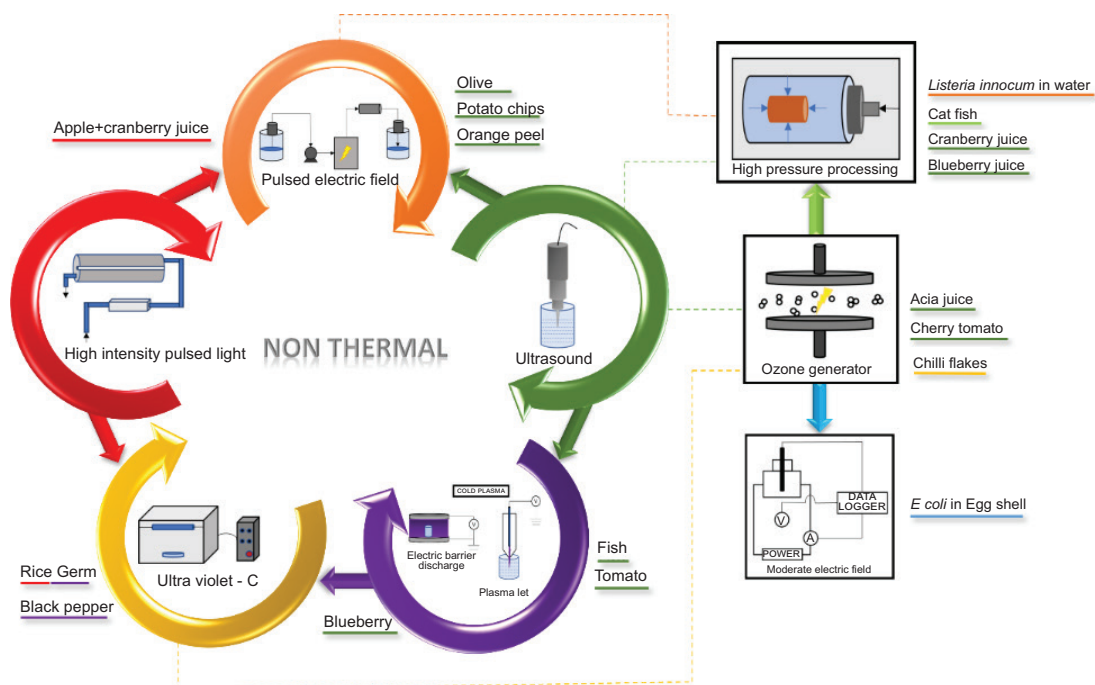


Figure 1. Nonthermal hurdle combinations and their applications.

Usually, the hurdle combination includes one nonthermal or thermal technique, which is combined with other hurdles such as preservatives, acidulants, enzymes, etc. (Basak and Chakraborty, 2022). To overcome the negative aspects of the above combinations, including the retention of chemical residues in some foods, the “nonthermal hurdle” approach is used. Some of the recent applications of nonthermal hurdle technologies in the food sector are listed in Table 1, which helps us understand the positive impacts of these technologies. The food processing sector is poised for significant growth in nonthermal processes. These methods offer consumers nutritious, wholesome food with improved textures, flavors, and colors (Allai *et al.*, 2023).

Effect of Nonthermal Hurdle on Microbial Inactivation

The major reason for spoilage in any food material is microorganisms. Inactivation of these spoilage-causing microorganisms without significant loss in nutritional parameters is achieved through nonthermal hurdle technology. The main purpose of hurdle technology is to prevent specific microorganisms from growing and stabilizing by exposing them to alternating or simultaneous environmental, physical, and chemical stresses (Aaliya *et al.*, 2021). Three primary mechanisms work together to accomplish this task: metabolic fatigue, stress response mechanism deprivation, and obstruction of equilibrium conditions (Pal *et al.*, 2017; Bigi *et al.*, 2023; Obileke *et al.*, 2022). The studies below not only focus on liquid food products but also on solid food materials. They examine the technique's negative effects on microbes and its positive impact on product characteristics.

In research by Chen *et al.* (2021), the nonthermal hurdle combination of thermosonication and high hydrostatic pressure was used, and the study focused on reducing the microbial load by destroying microorganisms in blueberry juice. For thermosonication, sound waves were created at 240 W and 40 kHz, with temperature combinations of 25°C and 45°C followed for 15 min each. Even though the name includes ‘thermo’ in sonication, the temperature was maintained below 45°C, so it falls under nonthermal technology. Similarly, high hydrostatic pressures of 400 and 600 MPa were applied for 5 min each. The study concluded that combinations of nonthermal technologies—pressure at 400 and 600 MPa with thermosonication at 25°C and 45°C—showed a reduction in microbial load below 1 log CFU/mL, along with the inactivation of enzymes like polyphenol oxidase. This combined effect of thermosonication and high hydrostatic pressure caused mechanical damage to the cell wall structure of microbes through pressure, cavitation, and free radical oxidation, leading to the inactivation of microbes. In a study by Anjaly *et al.* (2022) on pineapple juice, the shelf life was enhanced using ultrasound and

UV light with a wavelength of 254 nm as a hurdle combination. Ultrasound was operated at 33 kHz for 22.95 min, and UV light at 1.577 J/cm² for 10 min. A 5-log reduction in bacterial and yeast populations was achieved with the optimal ultrasound and UV combination. Ultrasound travels through the material as longitudinal waves, causing cavitation. The implosion of the bubbles produces shock waves that, in turn, destroy the cell walls and membranes of microorganisms and denature their DNA (deoxyribonucleic acid) through the sonolysis of liquid (Stepišnik Perdih, Zupanc, and Dular, 2019). When UV rays are absorbed by DNA, pyrimidine nucleotide bases undergo cross-linking. The creation of these dimers prevents further transcription and replication, ultimately resulting in cell death (Corrêa *et al.*, 2020). The combined action of UV exposure and ultrasonic waves results in a reduction of bacterial load, which can be attributed to two phases of inactivation: the first is ultrasonic cavitation, which destroys cell walls, and the second is UV exposure, which denatures DNA and causes cell death. The organoleptic quality retention was almost similar to fresh juice, along with the microbial reduction mentioned above (Anjaly *et al.*, 2022).

Hwang *et al.* (2023) conducted research involving three nonthermal hurdle combinations for microbial inactivation in granulated and powdered foods. The hurdles used were intense pulsed light (IPL), atmospheric plasma, and UV. IPL was applied with a fluence of 24.4 J/cm², voltage of 30 V, and a time duration of 30 min; atmospheric plasma was operated at 1 kV and 30 Hz, and UV light was at 253.7 nm, with 8 W per lamp and five lamps. A maximum of 1.33 ± 0.24 log microbial reduction was observed in sesame seeds. These combinations were also applied to black pepper powder and red pepper powder, which showed microbial log reductions of 0.41 ± 0.04 and 0.52 ± 0.05 , respectively. Due to variations in the surface properties of red and black pepper powders, the effects were less pronounced than those observed in sesame seeds. Free radicals, including free electrons, dissolved hydrogen peroxide, ozone, electric fields, acoustic shock waves, and ultraviolet light (UV), are all produced by plasma, and it is well known that UV only slightly contributes to the process of plasma decontamination. Therefore, the potency of reactive species raises the mechanical damage to microbial cells and enhances microbial inactivation. A study by Lara *et al.* (2022) on microbial reduction in fresh beef using a nonthermal hurdle combination of aqueous ozone and UV-C found that aqueous ozone at 0.9 ppm was sprayed, and UV-C was operated at 69 mJ/cm² for 30 s. This combination showed a 1.7 log reduction in *Escherichia coli* after 10 cycles, with a 1-h time gap between each cycle. To enhance antimicrobial action and promote cell death, the above combination was studied further. As microbes encounter the stationary growth phase, they release proteases that break down

Table 1. Recent applications of nonthermal hurdle technologies in food.

Types of food	Nonthermal hurdle combinations	Treatment parameters	Effects	Reference
<i>Disinfectant</i>				
Cherry Tomato	Plasma activated water (PAW) + Ultrasound (US)	PAW: Atmospheric air plasma jet, 2-7 kV, 5 and 10 min US: 40 kHz – 15 min	- Degradation of chlorothalonil fungicide concentration up to 89.29%. A higher reduction of up to 97.25% was recorded during storage. Because reactive species have a longer shelf life, PAW and US work together to create hydroxyl radicals that increase during storage and break down pesticides. - Does not affect the quality of fruit.	(Ali <i>et al.</i> 2023)
Vegetables (Spinach, bean celery, cabbage and tomato)	US + Ozone	US: 20 Hz and 40 Hz OZONE: 5 mg/L	- Removal of pesticides namely chlorpyrifos, carbofuran, difenoconazole, dimethoate, diniconazole, and isoprocarb ranging between 79.1% to 92.2%. - Free radicals produced during US+O3 oxidation enable efficient pesticide degradation in water and vegetables, influenced significantly by vegetable structure and surface area. - The rates of pesticide removal based on the surface area were as follows: spinach < cabbage < celery < bean < tomato. - Especially degradation of chlorpyrifos achieved by the S-P bond oxidation, chlorine atoms substitution, and cleavage of phosphoester bonds. - Spinach's chlorophyll content was slightly declined, most likely due to oxidation between chlorophyll and Ozone.	(Yang, Xue, and He 2024)
<i>Extraction</i>				
Almond extract	PEF + US	PEF: 1kHz, > 35 °C – 500 µs Electric field strength (EFS) – 18 kV/cm Flow rate- 40 mL/min US: 40 Hz, 200 W, 35 °C – 20 min	- Extracted almonds have increased total phenolics and other bioactive compounds including metal chelating agents. - This is due to the combination of electrical fields creating irreversible pores in membranes, enhancing extraction efficiency by removing barriers and US complements this by promoting the diffusion of intracellular compounds into the extraction medium.	(Manzoor, Zeng, and Rahaman 2019)
Grape stem	PEF + US	PEF: 1 Hz EFS – 1 kV/cm TT – 30 min US: 35 kHz – 15 min	Improved volatile and polyphenol yield of extraction from the grape stem.	(Niourtoglou <i>et al.</i> 2022)
Rosemary and Thyme	PEF + US	PEF: 10 Hz Specific PEF energy input – 0.36 and 0.461 kJ/kg US: 400 W, 24 kHz Specific energy - 409.31 kJ/kg – 4 min Extraction time: 12.48 min	Improved phenolic compound recovery and antioxidant capacity.	(Tzima <i>et al.</i> 2021)
<i>Drying</i>				
Shiitake mushroom (<i>Lentinus edodes</i>)	PEF + US	PEF: 20 kV, 1 Hz EFS – 1 kV/cm US: 40 kHz, 180 W -30 min Intensity – 1.63 W/cm	- Improved drying efficiency. PEF-US treatment enhances the rate of drying and diffusion coefficients due to electroporation's uniform effect and US-induced cavitation improving homogeneity. - Due to reduced drying time improved quality of the product with retention of its nutritional value achieved.	(Li <i>et al.</i> 2021)

(continues)

Table 1. Continued.

Types of food	Nonthermal hurdle combinations	Treatment parameters	Effects	Reference
<i>Quality and other parameters</i>				
Spinach juice	PEF + US	US: 40 Hz, 200 W, 30 °C – 21 min PEF: 1 kHz, 30 °C, 335 µs EFS – 9kV/cm Flow rate – 60 mL/min	• Inactivation of peroxide. • Increase in total flavanols and phenolics. PEF treatment enhances intracellular metabolite extraction by permeabilizing cell membranes. Also, by US releases bound phenolic compounds via cavitation, thereby increasing total phenolic yield. • Slight change in color. This is due to cavitation-induced mechanical forces during ultrasonication increases cloud value, possibly due to homogenization and breakdown of larger molecules in spinach juice.	(Manzoor et al. 2021)
Potato chips	PEF + US	PEF: 2 Hz, 15 °C, EFS – 1 kV/cm US: Amplitude – 25 µm Time – 180 sec Specific energy – 40 kJ/kg	• Acrylamide content reduction up to 66%. • Combining PEF and US accelerates moisture removal, shortening frying time, reducing acrylamide formation, and maintaining consistent surface temperatures for improved product quality.	(Ostermeier et al. 2020)
Fresh cut Lettuce	Ozone + UV-C	OZONE: 5 mg/L, Time: 5 min UV-C: 254 nm, Fluence: 0.2, 0.4, and 0.8 kJ/m ²	• Weight loss was prevented above 25% during cold storage. • Improved the quality of texture due to reduced weight loss • Crispiness was improved up to 35%. Reduced degradation of color, most likely as a result of the physiological degradation that was encouraged by the combined effects of O3 and UV-C.	(Templaxxis et al. 2023)
Milk	US + PEF or HPP	Homogenization – US: 20 kHz at 40 °C Intensity: 0.25, 0.5, and 1 kJ/mL; Pasteurization – HPP: 120 kJ/kg, 20 kV/cm; HPP: 600 MPa, 2 min at 10 °C	• US reduced the size of the fat globule (0.22 ±0.02 µm) at 1 kJ/mL. • After storing for a period of 28 days, milk treated with HPP showed high yellowness in color. • Both treatments did not affect other quality parameters of milk.	(Astráin-Redín et al. 2023)
Strawberry juice	PEF + High power ultrasound (HPU)	PEF: 30 kV/cm, 100 Hz, Time: 1.5, 3, and 4.5 min HPU: 25% amplitude and 50 % pulse, Time: 2.5, 5 and 7.5 min	• Bioactive compounds like hydroxycinnamic acid and total phenols are the most stable. • Followed by condensed tannins and flavanols with good stability. • Shorter treatment time showed better activity of antioxidants and stability of bio-actives present in strawberries.	(Bebek Markovinić et al. 2023)
Dried Pistachios	UV + CP	UV: 354 nm, current intensity: 0.25 A CP: 80 W, Time: 10 and 15 min	• Deactivation of fungi. In plasma sterilization, reactive species (RS) are the main antimicrobial agents, while UV radiation primarily acts by causing DNA mutations in microbes. • The investigation of the samples' pH and radical scavenging action of DPPH revealed no significant alterations in it. • Maintained the quality and improved the shelf life of the sample.	(Zeraatpisheh et al. 2023)

the connective tissue between the meat's muscle fibers, enabling bacterial penetration in the meat. According to one theory, light photons on the meat may scatter in ozonated water, interfering with their journey to the meat's surface, where bacteria reside during their rapid growth phase. Unlike UV light alone, ozone can cause oxidative damage to other tissues after processing (Corrêa *et al.*, 2020). The combined effectiveness of these two antimicrobial strategies against microbes was found to be lower than their individual effectiveness (Harikrishnan *et al.*, 2023; Dogu-Baykut and Gunes, 2022). This research underscores the significance of choosing the appropriate pairing of methods for concurrent application during processing. A few more studies on microbial inactivation in various foods using nonthermal hurdles are listed in Table 2.

Nonthermal Hurdle as Disinfectant Reducing the Chemical Residue

Fresh produce, including vegetables and fruits, are essential components of the human diet due to their numerous nutritional and health benefits. In addition to demanding high-quality, fresh-like products, consumers are becoming increasingly aware of the safety risks associated with consuming fruits and vegetables (Deng *et al.*, 2020). To ensure microbiological safety and extend the shelf life of fresh produce, it is crucial to eliminate microorganisms during post-harvest handling. Today, a variety of disinfection techniques are used. The most commonly used antimicrobial sanitizer in the food industry is chlorine. However, halogenated organic compounds, such as chloroform, can be produced when chlorine reacts with organic materials, and these compounds are linked to human rectal and bladder cancer (Roobab *et al.*, 2022). Furthermore, treating water with chlorine releases chlorine vapors and forms trihalomethanes and haloacetic acids, two byproducts that may cause cancer (Praeger, Herppich, and Hassenberg, 2018). Similarly, organic acids destroy microorganisms by lowering the pH of their environment and inside their cells, which disrupts membrane permeability and transport. However, due to their low concentration or short treatment duration, organic acids have relatively low antimicrobial efficacy and fail to effectively control microorganisms (Deng *et al.*, 2020). Additionally, using high concentrations of organic acids has drawbacks, such as altering the flavor and aroma of fruits and vegetables and potentially corroding human tissue and medical equipment (Khan *et al.*, 2017). One drawback of sanitizer washing is the need for large amounts of water, which can lead to environmental contamination and pathogen cross-contamination. Moreover, the moisture left behind after washing fosters the growth of mold. Since thermal treatments cause undesirable physiological decay and metabolic reactions,

such as tissue weakening, color degradation, and nutrient depletion, there has been a growing interest in developing non-thermal physical technologies to reduce microbial loads on fruits and vegetables (Deng *et al.*, 2020).

Retention of chemical residues in fruits and vegetables has always been a potential problem in processing. Farmers use pesticides and fungicides to mitigate damage from pests, such as insects and microbes, aiming to enhance crop yield. However, these chemicals are not entirely removed through normal washing procedures. Nonthermal hurdle technology is employed to reduce chemical residues in fruits and vegetables. The most commonly used fungicide, chlorothalonil, has been linked to detrimental effects on human health (Jones *et al.*, 2020). In soil and plant systems, chlorothalonil can persist and break down depending on factors such as the amount applied, the planting schedule, soil characteristics, climate, and the use of fertilizers. Gaining more insight into its behavior in soil and vegetable systems could help develop protocols that optimize fungicide usage, improve food safety, and reduce environmental pollution (Zhang *et al.*, 2021). A study conducted by Ali *et al.* (2022) aimed to reduce the fungicide residue of chlorothalonil in tomatoes. The nonthermal hurdle combination of ultrasound and plasma-activated water was used. Plasma-activated water was generated using a plasma jet operated at 220 V and 50 kHz, with 250 mL of water for each batch. Similarly, ultrasound was applied after the activation of water using the plasma jet, operating at 500 W and 40 kHz. The tomatoes, weighing between 28 and 35 g, were soaked in plasma-activated water for various time intervals followed by ultrasound treatment for 15 min. The combined treatment of plasma-activated water (10 min) followed by ultrasound (15 min) showed the highest reduction in fungicide residue, with a reduction of 89.29%. The results indicate that the combination of nonthermal technologies led to a greater degradation of the fungicide chlorothalonil in tomatoes (Ali, Cheng, and Sun, 2021). This was achieved with minimal to no textural changes and retention of nutritional parameters (Ali *et al.*, 2023).

Nonthermal Hurdles in Particular Composition of Food

Based on composition, foods are classified into solid, liquid, and semisolid categories. Below are some examples of nonthermal hurdles applied to solid and liquid foods individually, with a detailed overview of their effects.

Effect of nonthermal hurdle technologies in solid foods

Nonthermal technologies have been used as pre-treatment in combination with traditional treatments in food processing operations (Shiekh, Zhou, and Benjakul, 2021). However, in recent years, nonthermal technologies

Table 2. Application of nonthermal hurdle technologies in microbial inactivation.

Food/ingredient	Nonthermal hurdle applied	Treatment parameters	Effects	Reason	Reference
Black peppercorns	Cold plasma (CP) + UV-C	CP: 10.3 kV, 15 kHz Treatment time (TT): 22.1 min UV-C: 5 lamps, 253.7 nm, 6 W – 20 min Intensity: 616 $\mu\text{W}/\text{cm}^2$	Decontamination of microorganisms (indigenous bacteria and <i>B. tequilensis</i> spore).	Simultaneous application of UV and CP can effectively destroy microbial cell membranes by breaking down bonds and etching the membrane. This allows UV light and CP-reactive species to penetrate the damaged membrane and react with cell contents, including DNA.	(Bang et al. 2020)
Catfish filets	Ozone water (OW) + Ultrahigh pressure (UHP)	OW: Immersion – 13.28 mg/l – 10 min UHP: 200 MPa – 10 min	- Decreased the microbial load during refrigeration mainly on <i>Enterobacteriaceae</i>, <i>Pseudomonas</i>, LAB and HSPB. - Decreased total volatile base nitrogen (TVBN) value.	This hurdle could be explained by the extremely high pressure that further pierced the oxidation-damaged cells, causing irreversible degradation.	(Ling, Zhou, et al. 2022)
Oil in water emulsion	Pulsed electric field (PEF) + High pressure ultrasound (HPU)	PEF: 30 kV, 25 °C, 70 μs HPU: 24 kHz – 3 min	Inactivation of microbes mainly <i>E. coli</i>, <i>Aspergillus niger</i>, and least on <i>Bacillus pupilis</i>.	PEF induces membrane damage in microorganisms, increasing their susceptibility to mechanical cell stress induced by cavitation in subsequent treatments.	(Gomez-gomez et al. 2021)
Blueberry	US + CP + peracetic acid (PAA)/free chlorine (FC)	CP: 10 kHz and 200 Hz US: 25 Hz and 400 Hz PAA: 80 ppm FC: 10 ppm	- Improved disinfectant efficacy (<i>E. coli</i> O157:H7, <i>Salmonella typhimurium</i>). - Improved antioxidant activity.	- US induces cavitation bubbles creating shear force and high pressure to puncture bacterial membranes. Reactive oxygen and nitrogen species production by CP, intensifies membrane disruption and severe intracellular damage. Additionally, PAA and FC exhibit antibacterial properties by causing enzyme inactivation, DNA damage, and oxidative harm to cell membranes. - By scavenging reactive oxygen species (ROS), in-package CP can activate the antioxidant system of blueberries and reduce the likelihood of quality loss.	(Wang and Wu 2022)
Rice germ	Plasma jet + Pulsed light (PL) + UV-C [PPU]	APPJ: 1 kV, 30 Hz PL: 1.8 – 5.0 kV UV-C: 8 W, 5 lamps, 253.7 nm Treatment Time (TT): 7 min	- Decontamination of microorganisms increases with increases in treatment time and decreases with a decrease in sample. - The natural bacteria, mold, and yeast numbers were initially 3.7 and 5.7 log CFU/g but were later reduced to 2.0 and 1.0 log CFU/g.	Applying plasma and IPL simultaneously enhances microbiological cell membrane damage: reactive species of plasma etch the membrane, while IPL cleaves bonds. This synergistic damage facilitates easier penetration of reactive species and UV into the cell, reacting with intracellular elements such as DNA.	(Lee et al. 2021)

Crayfish	US + Plasma activated water (PAW)	US: 40 kHz Plasma: Air pressure: 0.18 MPa, flow rate: 20-30 L/min Treatment Time: 0, 20, 40 or 60 min	1.17 log CFU/g total viable count reduction at 40 min treatment time. - Natural biota showed a significant reduction which is present in crayfish. - Elongated storage period. - Reduced texture and color deterioration. - In protein content, improvement of β-sheet content and decreased α-helix content was seen. - Reduced migration of water and improved the bond water stability in crayfish.	- The cavitation was typically accompanied by high temperatures and localized pressure sites, which may have caused cytoplasmic membranes of bacteria to become delicate and made it easier for reactive species to enter cell walls. - The greater aggregation of myofibrillar proteins of crayfish as a result of the compression by mechanical shockwaves brought on by the US may be connected to the higher hardness values. - The change in protein structures brought about by US and PAW interventions, could improve the biological qualities of proteins.	(Sun <i>et al.</i> 2023)
Wastewater	US + Ozone = "Sonozone"	US: 4.8 kHz at 18 °C, Time: 30, 90, 300, and 600 s OZONE: 1.46 mg/L, Time: 60 and 120 s for <i>Pseudomonas</i> sp.; 30 and 60 s <i>Enterococcus</i> sp.; 15 and 30 s for <i>E. coli</i> ; 30 and 45 s for <i>S. Enteritidis</i> .	5 log reduction compared to an initial count of microbes within five min. - Energy consumption was reduced by up to 67% compared to individual treatment.	Bacterial clusters can be broken up into individual cells by ultrasound, which increases their ozone sensitivity. Furthermore, ionic bonds within the cell membranes are broken by the implosion of bubbles formed by cavitation, weakening the cells' resistance to oxidative pressures.	(Moretti, Alessandro <i>et al.</i> 2023)

have been employed as a hurdle to overcome the minor to major losses that occur during traditional techniques such as thermal and chemical treatments (Bigi *et al.*, 2023). Below are a few studies on the effect of nonthermal hurdles on solid foods. Johnson *et al.* (2022) utilized plasma-functionalized water combined with ultrasound as a nonthermal hurdle on *Larimichthys polyactis*—a small yellow croaker (fish). The study focused on the functional and bioactive properties of the fish. Plasma-functionalized water was obtained by treating 20 mL of double-distilled water between dielectric barrier discharge electrodes, 5 mm apart, with a plasma generator operating at a voltage of 70 V for 8 min. Ultrasound was then applied after plasma-functionalized water treatment, operating at 500 W and 40 kHz for 4 min. The combination of plasma-functionalized water and ultrasound treatment caused partial denaturation of the protein structure, which led to increased peptide yield with improved solubility, while lowering emulsification and foaming abilities. Additionally, the treatment enhanced enzymes with specific antioxidant properties. The hurdle combination of ultrasound and plasma-functionalized water was also applied to *Pampus argenteus* (silver pomfret) by Johnson, Sun, Cheng, and Li (2022). Plasma-functionalized water was prepared by treating 20 mL of double-distilled water between dielectric barrier discharge electrodes. It was operated at 70 V with a frequency of 10 kHz for 8 min using atmospheric cold plasma. Ultrasound treatment was then applied at 500 W and 40 kHz for 5 min at room temperature (25°C). The treated fish were vacuum packed and stored at 4°C for 15 days. Storage studies showed modifications in myofibrillar proteins, improved nutritional retention, and a biomedical index of fatty acids and lipids, with a lowered pH of 5.7. This study demonstrated the improvement in the storage life of the treated fish while retaining their nutritional parameters through the use of nonthermal technologies as a hurdle.

In a study conducted by Mello *et al.* (2021), the combination of pulsed electric fields (PEF) and ultrasound was applied to orange peels, followed by drying, to investigate their effects on quality parameters. The pulsed electric field operated at an electric field strength of 1.20 kV/cm and a frequency of 10 Hz for durations of 200 μ s and 600 μ s, while ultrasound was operated at 20.5 kW/m³. This nonthermal hurdle was applied as a pre-treatment, followed by drying at 50°C. The hurdle effect of the pulsed electric field for 200 μ s, combined with ultrasound as a pre-treatment before drying, resulted in the shortest drying time while retaining the original color of the orange peel. Additionally, it helped preserve phenolic content and ascorbic acid. However, the pulsed electric field treatment for 600 μ s led to a reduction in antioxidant activity. In conclusion, the combination of pulsed electric field and ultrasound shortened drying time and

preserved important nutritional compounds, when compared to the individual treatments. In a recent study by Harikrishnan *et al.* (2023), the combination of UV and ozone was applied to study the hurdle effect on the textural and structural properties of dough. The dough was made from de-oiled rice bran, virgin coconut oil cake (VCO), corn starch, wheat bran, and guar gum as binding agents. The dough was treated with UV at 1000 $\mu\text{W}/\text{cm}^2$ for 15 min and aqueous ozone at 3 mg/L for 5 min at pH 4. A microbial reduction of 5.2 logs was observed compared to the untreated sample. Significant reductions in yeast/mold count and bacterial load were noted. The textural and structural properties also improved in the treated dough compared to the untreated sample. A study on cleaning and microbial inactivation in crayfish (*Procambarus clarkii*) was conducted by Ling, Tan, *et al.* (2022) using a hurdle combination of ozone water and ultrasound. Ozone water at a concentration of 26.6 mg/L for 20 min and ultrasound at an intensity of 200 W for 10 min were used. The most dominant microbe in untreated crayfish, *Chrysoebacterium*, was significantly reduced by this treatment. All microbial communities, including total viable count (TVC), psychrophilic viable count (PVC), mesophilic viable count (MVC), hydrogen sulfide-producing bacteria (HSPB), yeast and mold, and *Pseudomonas*, were reduced. Overall, the quality of the crayfish was not affected by this combination of techniques.

The investigation into solid foods processed using non-thermal technologies as hurdles has shown several beneficial outcomes. These technologies have demonstrated positive effects on the treated foods, enhancing yield, preserving nutritional parameters, and extending the storage life of certain food materials. Similarly, numerous studies have explored the application of various non-thermal technologies as hurdles across different food types, consistently yielding positive results in several key parameters. Ongoing research continues to explore the potential of these hurdle combinations across diverse food categories, promising further insightful findings in the coming years.

Effect of nonthermal hurdle technologies on liquid foods

Nonthermal hurdle combinations have also been applied to treat various liquid foods in the food processing line (Manzoor *et al.*, 2021). In a study by Hales *et al.* (2022), the microbial inactivation of milk was explored using a combination of high-intensity ultrasound (HIU) and UV-A light. HIU was operated at 500 W, 20 kHz, while UV-A had an intensity of 6000 $\mu\text{W}/\text{cm}^2$ and a wavelength of 365 nm. Various time combinations were tested, with HIU for 30 s and UV-A for 15 min showing the best microbial reduction. The combination resulted in a reduction of 0.69 ± 0.04 log in microbial load, effectively inactivating both gram-positive and gram-negative

microbes in milk, with only slight changes in pH and color. Similarly, a study by Sahoo & Chakraborty (2023) investigated the inactivation of pectin methyl esterase (PME) in sweet orange juice (*Citrus sinensis* L. Osbeck). PME is responsible for the destabilization of the cloudy nature of orange juice. In this study, pulsed light was combined with ultrasound. Various voltage and time combinations were tested, both individually and in combination. The operating condition of 283 s at 2.84 kV resulted in 98.5% PME inactivation, while ultrasound at 108 W for 9 min achieved an 82.5% reduction in PME. However, the combination of pulsed light at 2.4 kV for 180 s and ultrasound at 80 W for 360 s resulted in 98.3% PME inactivation. This combination reduced the operating time and voltage required, achieving excellent PME inactivation. It also led to more than a 5-log reduction in the natural microbiota, 99.4% retention of phenolic compounds, and only a 5% loss in vitamin C. Sensory parameters and bioactive compounds were largely unaffected, with only minimal degradation in color observed.

A study by Bebek Markovinović *et al.* (2024) examined the influence of two nonthermal treatments on antioxidant activity and bioactive components in strawberry juice. The hurdles used were high-power ultrasound and pulsed electric field (PEF). Ultrasound was operated at 25% amplitude and 50% pulse for various durations, while PEF was applied at a strength of 30 kV/cm and a frequency of 100 Hz for different time intervals. The results indicated that shorter treatment times of ultrasound combined with PEF favored the preservation of bioactive compounds in the juice. The highest yield of condensed tannins, flavonols, total phenolic content, and antioxidant capacity was achieved with a shorter ultrasound treatment time of 2.5 min, based on the optimization of the hurdle parameters. This study suggests that functional strawberry juice can be produced by fine-tuning the parameters of the hurdle technology. Overall, nonthermal technologies can be effectively used as hurdle treatments in both solid and liquid foods, leading to improved yield, retention of nutritional parameters, and microbial load reduction, all contributing to enhanced shelf life. This approach offers food processing industries the opportunity to optimize process parameters and improve efficiency.

Nonthermal Hurdle in Extraction

In the food and pharmaceutical industries, extraction is a method used to separate bioactive molecules from raw materials for use as active ingredients. Conventional extraction techniques include solvent extraction, steam or water distillation, maceration, squeezing or cold processing, and Soxhlet extraction (Zia *et al.*, 2020). However, these traditional methods have several drawbacks,

such as high energy consumption, excessive use of solvents, long extraction times, and low extraction yields (Wani *et al.*, 2021). Consequently, there is an increasing demand for innovative extraction techniques that use less solvent, operate more efficiently, and yield higher extraction rates (Zia *et al.*, 2020). Generally, extraction mechanisms involve the use of chemical agents and thermal treatments to enhance the yield of the desired solvent. However, chemical treatments can alter product characteristics and leave behind chemical residues in the extract, while thermal treatments may lead to the loss of nutritional components and volatile compounds.

Recently, there has been growing interest in innovative technology-assisted extraction methods (Wiktor *et al.*, 2018; Tzima *et al.*, 2021). These methods, which include non-thermal techniques such as pulsed electric field (PEF), supercritical fluid (SF), ultrasound (US) and moderate electric field (MEF) assisted extraction, as well as thermal methods like microwave (MW) and pressurized liquid (PL) extraction, have proven to be effective. Compared to traditional extraction methods, these advanced techniques offer several advantages, including reduced extraction times, lower energy consumption, reduced costs, and less use of organic solvents. In microwave extraction, the interaction between microwave energy and moisture in the matrix leads to evaporation, which creates pressure within the cell walls, causing them to rupture and release bioactive compounds. However, microwave radiation can result in the loss of heat-sensitive compounds and reduced extraction yields, as prolonged exposure and high power levels may trigger heat-induced degradation and enzymatic activity, significantly affecting bioactive plant constituents (Zia *et al.*, 2020). Pressurized liquid extraction is considered an effective and environmentally friendly method, using solvents like ethanol and water to extract bioactive compounds. While it offers advantages such as reduced solvent use, an oxygen- and light-free environment, and shorter operation times, the process can be costly in terms of industrial energy requirements. Supercritical fluid extraction, although considered clean, can produce extracts that contain impurities, making purification more challenging (Leal *et al.*, 2020).

To address the challenges associated with traditional extraction methods, nonthermal hurdle technologies have been increasingly adopted or even replaced conventional techniques (Wiktor *et al.*, 2018; Wani *et al.*, 2021; Z. Zhang *et al.*, 2018). Pulsed Electric Field (PEF) is widely recognized as an energy-efficient technique for permeabilizing cellular membranes, and it has also been suggested as a novel stressor that can stimulate the development of bioactive substances. Ultrasound (US), known for its ability to disrupt cell membranes through pressurized sound wave transmission and cavitation, has been

shown to enhance the recovery of target metabolites. US is considered a clean, eco-friendly process that facilitates the extraction of active ingredients at low temperatures, thus reducing the breakdown of heat-sensitive materials and shortening extraction times (Tzima *et al.*, 2021). The Moderate Electric Field (MEF) method has been found particularly effective in extracting colorants from plants. By applying voltage across the food material, MEF damages the cell membrane, altering its permeability and causing cell rupture. This electroporation increases the extraction yield by allowing the cells to absorb exogenous molecules more easily (Wani *et al.*, 2021). These non-thermal hurdles not only effectively inactivate microbes but also serve as valuable pre-treatment techniques in food processing operations, saving both time and energy (Shiekh, Zhou, and Benjakul, 2021; Leal *et al.*, 2020). As a result, they enhance the efficiency and economy of the overall process. One such application of these technologies is in the extraction process, as discussed below.

In a study by Grillo *et al.* (2022), the combination of ultrasound and pulsed electric field (PEF) was utilized as a nonthermal hurdle for the continuous extraction of virgin olive oil. Traditionally, the olive oil extraction process includes a step known as “malaxation,” where olive paste is slowly and continuously kneaded to disperse the emulsion formed during crushing and to facilitate mixing and coalescence (Clodoveo, 2019). In this study, ultrasound was applied at a power of 600 W and a frequency of 22 kHz, while the pulsed electric field was operated at 8 kV for 30 μ s with a frequency of 15 Hz. The combination of these treatments caused acoustic cavitation and electroporation, which helped improve the oil yield from 16.3% to 18.1%. This nonthermal hurdle combination effectively replaced the traditional malaxation step. While ultrasound treatment alone resulted in a yield increase of 17.8%, the combined treatment further enhanced the yield. In addition to yield, the treatments also improved the levels of minor components such as tocopherols and tocotrienols by 15.9%, thereby enhancing the quality and commercial value of the extracted virgin olive oil. This nonthermal hurdle technology has also been successfully applied to oil extraction from other food materials, demonstrating improved yields, retention of nutritional parameters, and enhanced quality of the extracted oil. In a separate study by Hossain *et al.* (2014), pulsed electric field (PEF) and pulsed light (PL) were used as pre-treatments for solid-liquid extraction of steroidal alkaloids from potato peels. The PEF treatment was applied at a field strength of 0.75 kV/cm and a pulse duration of 600 μ s, resulting in a significant increase in the yield of steroidal alkaloids, reaching 1856.2 μ g/g from dry potato peels, a 99.9% increase compared to untreated peels. Similarly, pulsed light (PL) also enhanced the extraction of glycoalkaloids and aglycone alkaloids, with treatment fluences of 7.86 J/cm² and 9.38 J/cm². However, the PEF

pre-treatment produced a higher yield than PL, demonstrating its greater effectiveness in enhancing extraction efficiency.

Most Followed Nonthermal Hurdle Combinations

Nonthermal technologies are proving to be more efficient than conventional thermal treatments across various aspects of food processing. Their effectiveness is further amplified when used in combination with other nonthermal technologies as part of a hurdle approach. Although several nonthermal technologies are already in commercial use within food processing industries (Anand *et al.*, 2022), achieving optimal combinations requires further research and development. Understanding the interplay of individual technologies and their combined effects through trial and error is crucial for enhancing treatment outcomes (Bigi *et al.*, 2023). In this context, numerous studies have been conducted to develop specific combinations of nonthermal hurdles tailored to different types of food. These hurdle combinations serve a variety of objectives, including preservation, microorganism inactivation, enhancement of nutritional parameters, retention of sensory attributes, improvement in extraction efficiency, and overall protection of food quality (Anand *et al.*, 2022). Among these combinations, several have emerged as particularly popular and effective for specific food applications.

Ultrasound is one of the most prominent and promising nonthermal technologies, particularly when used in combination with other nonthermal methods (Ostermeier *et al.*, 2020; Singla and Sit, 2021; Wang and Wu, 2022). Combining ultrasound with various techniques has been shown to reduce processing time and energy consumption (Beitia *et al.*, 2023). One of the most widely used combinations is plasma-activated or plasma-functionalized water with ultrasound. Plasma is a distinct state of matter, formed when a gas reaches a temperature high enough to ionize (Mayookha *et al.*, 2023). Plasma-activated water is produced by treating double-distilled water under plasma, typically using dielectric barrier discharge (DBD) or a plasma jet method (Wang and Wu, 2022). DBD plasma is especially popular due to its broad range of applications, reduced heat generation, and ease of operation (Wu *et al.*, 2023). Plasma inherently contains reactive species, including excited particles and UV radiation (Kaavya *et al.*, 2021), which contribute to its effectiveness. DBD plasma is also advantageous for sanitizing freshly packaged produce (Wang and Wu, 2022). Plasma-activated water is rich in reactive oxygen and nitrogen species (RONS) and other free radicals that can cause surface etching on microbial cell walls or food materials (Chakka, Sriraksha, and Ravishankar, 2021; Johnson, Sun, Cheng, and Wang, 2022; Roobab *et al.*, 2022).

When combined with ultrasound, these properties are further enhanced, leading to improved treatment efficiency. Ultrasound induces cavitation in food materials through the formation of microbubbles, driven by the compression and rarefaction cycles of high-frequency sound waves. This process is more potent and effective compared to other nonthermal technologies (Jadhav, Annapure, and Deshmukh, 2021).

Ultrasound is not only combined with plasma but also with other nonthermal technologies, such as high hydrostatic pressure and pulsed electric fields, to enhance food processing (Beitia *et al.*, 2023). While ultrasound can be paired with various nonthermal technologies, the combinations mentioned above, as illustrated in Figure 2, are the most commonly used. High hydrostatic pressure is effective at damaging microorganisms and denaturing specific enzymes. However, for complete enzyme denaturation, it is often combined with ultrasound treatment (Singla and Sit, 2021). Similarly, pulsed electric fields are frequently used as a pre-treatment followed by ultrasound to improve quality retention in food products (Ntourtoglou *et al.*, 2022; Pandiselvam *et al.*, 2023). The mode of action in pulsed electric fields involves electroporation, where externally applied electric fields create pores in the cell walls and membranes. This process increases cell permeability, making it easier for intracellular contents, primarily water, to pass from the cell into the extracellular environment (Katsimichas *et al.*, 2023). Factors such as reactor geometry, temperature, exposure time, power intensity, and frequency affect the bactericidal efficacy of ultrasound, and these parameters need to be optimized for better results (Bigi *et al.*, 2023; Bahrami *et al.*, 2020). When ultrasound is combined with high hydrostatic pressure or pulsed electric fields as pre-treatments, processing time is reduced, temperature rise is minimized, and the overall results improve. While each nonthermal technology yields good results individually, the shift towards nonthermal hurdle technologies is becoming more prevalent to achieve superior outcomes (Gomez-gomez *et al.*, 2021).

Future Prospects and Challenges

Non-thermal treatments have become a central focus in food industry research due to increasing consumer demand for safe, nutrient-rich, and microbe-free foods. These technologies are considered more environmentally friendly and less harmful to food quality compared to traditional methods. As minimal processing techniques, non-thermal technologies are gaining recognition for their ability to preserve the authenticity of food while enhancing its texture and organoleptic qualities. However, harsh processing conditions, such as high temperatures, long treatment times, and high energy inputs,

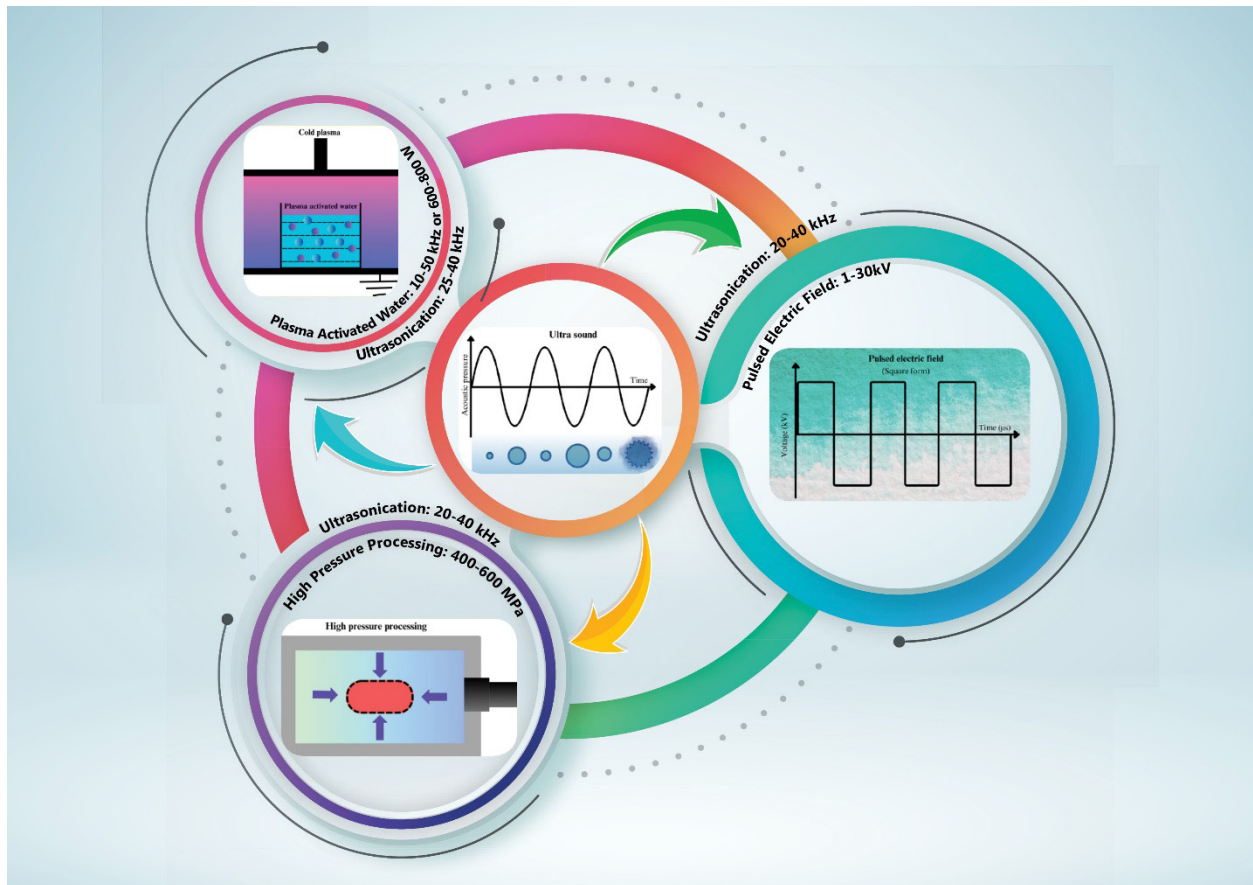


Figure 2. Extensively utilized nonthermal hurdle combinations.

often compromise sensory attributes like aroma, color, texture, taste, and nutritional value. As such, no single non-thermal technology can guarantee optimal food quality across all sensory aspects. This is where hurdle technology comes into play, offering a more efficient processing approach to ensure food safety, health benefits, and improved overall quality (Zhang *et al.*, 2018). Research on non-thermal techniques and hurdle technology continues to be a dynamic area of study, with ongoing efforts to optimize their performance and ensure food product safety without compromising quality. Variations of these preservation methods are continuously tested in laboratories and pilot projects to refine their effectiveness (Bigi *et al.*, 2023).

The advancement of nonthermal techniques in the food industry hinges on several key factors, including the development of machinery capable of processing large quantities of food, a deeper understanding of the underlying mechanisms of these technologies, the establishment of processing standards, and addressing consumer misconceptions about their effectiveness. Once these challenges are overcome in a structured and strategic manner, nonthermal technologies will have greater

potential for expansion and commercialization. This will enable the food industry to offer consumers safe, nutrient-rich products with appealing colors and sensory qualities (Jadhav, Annapure, and Deshmukh, 2021). However, the high initial investment costs and the need for skilled personnel for most hurdle technologies present barriers, making them costly and time-consuming. Therefore, future research should focus on improving the cost-effectiveness of these combined nonthermal treatments to ensure their widespread adoption in the food industry (Bigi *et al.*, 2023; Aaliya *et al.*, 2021).

Non-Thermal Technologies and Their Contribution to Sustainability Aligned with SDGs

Non-thermal food processing technologies are increasingly recognized for their significant contribution to global sustainability by aligning with multiple Sustainable Development Goals (SDGs). High Hydrostatic Pressure (HHP) minimizes energy usage and food waste, supporting SDG 12 (Responsible Consumption and Production) and SDG 2 (Zero Hunger) by improving food preservation without excessive energy consumption or

material waste. Pulsed Electric Fields (PEF) enhance energy efficiency and nutrient retention in food processing, supporting SDG 13 (Climate Action) and SDG 3 (Good Health and Well-Being) by preserving the nutritional content of food. Ultrasound processing promotes more sustainable practices by reducing water and energy consumption, contributing to SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy), ensuring more efficient use of resources during food processing. Cold plasma provides a chemical-free decontamination method, which helps to reduce agrochemical usage, thereby contributing to SDG 15 (Life on Land) promoting safer, more sustainable agricultural practices. It also advances SDG 12 by reducing the need for harsh chemical treatments in food processing. UV processing is an energy-efficient, eco-friendly sterilization method that helps reduce resource consumption, supporting SDG 7, SDG 6, and SDG 13 by offering a low-energy alternative to traditional sterilization methods. Together, these non-thermal technologies not only reduce resource consumption but also preserve food quality and minimize waste and emissions. They provide innovative solutions that help meet global challenges related to sustainable food production and consumption, improving both environmental and human health outcomes.

Conclusion

The integration of nonthermal hurdle technologies marks a major breakthrough in the food processing industry, offering a wide range of benefits that address both consumer demands and the limitations of traditional thermal methods. These technologies effectively enhance microbial safety, extend shelf life, and preserve the nutritional quality and sensory attributes of food products. By combining various nonthermal techniques such as ultrasound, high hydrostatic pressure, pulsed electric fields, and others within hurdle strategies, food processors can achieve superior results compared to relying on individual methods alone. The synergistic effects of these technologies help mitigate the drawbacks commonly associated with chemical additives and thermal processing, allowing for the production of safer, high-quality foods that retain their fresh taste and nutritional value. As these technologies continue to evolve, ongoing research and development are crucial for optimizing their efficacy. Expanding their application across different types of food, reducing chemical residues, and improving their scalability will be key to meeting the growing demand for minimally processed, nutritious foods. Furthermore, the adoption of nonthermal hurdle technologies contributes to the sustainability of the food industry by reducing energy consumption, waste, and the reliance on harmful chemicals. In summary, nonthermal hurdle technologies not only enhance food safety and

quality but also foster more sustainable practices in the global food supply chain. With continued innovation and research, these technologies hold the potential to revolutionize food processing, providing consumers with healthier, safer, and more environmentally friendly food options.

Authors Contributions

All authors contributed equally to this paper.

Conflicts of Interest

None.

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References

- Aaliya, B., Valiyapeediyekkal Sunooj, K., Navaf, M., Parambil Akhila, P., Sudheesh, C., Ahmed Mir, S., Sabu, S., Sasidharan, A., Hlaing, M. Theingi, & George, J. (2021). Recent Trends in Bacterial Decontamination of Food Products by Hurdle Technology: A Synergistic Approach Using Thermal and Non-Thermal Processing Techniques. *Food Research International*, 147, 110514. <https://doi.org/10.1016/j.foodres.2021.110514>
- Al-Hilphy, A. R., Abdulstar, A. R., & Gavahian, M. (2021). Moderate Electric Field Pasteurization of Milk in a Continuous Flow Unit: Effects of Process Parameters, Energy Consumption, and Shelf-Life Determination. *Innovative Food Science and Emerging Technologies* 67, 102568. <https://doi.org/10.1016/j.ifset.2020.102568>
- Ali, M., Cheng, J. H., & Sun, D. W. (2021). Effect of Plasma Activated Water and Buffer Solution on Fungicide Degradation from Tomato (*Solanum Lycopersicum*) Fruit. *Food Chemistry*, 350, 129195. <https://doi.org/10.1016/j.foodchem.2021.129195>
- Ali, M., Cheng, J. H., Tazeddinova, D., Aadil, R. M., Zeng, X. A., Goksen, G., Lorenzo, J. M., Esua, O. J., & Manzoor, M. F. (2023). Effect of Plasma-Activated Water and Buffer Solution Combined with Ultrasound on Fungicide Degradation and Quality of Cherry Tomato during Storage. *Ultrasonics Sonochemistry*, 97, 106461. <https://doi.org/10.1016/j.ultsonch.2023.106461>
- Ali, M., Sun, D., Cheng, J., & Johnson, O. (2022). Effects of Combined Treatment of Plasma Activated Liquid and Ultrasound for Degradation of Chlorothalonil Fungicide Residues in Tomato. *Food Chemistry*, 371, 131162. <https://doi.org/10.1016/j.foodchem.2021.131162>
- Allai, F. M., Azad, Z. R. A. A., Mir, N. A., & Gul, K. (2023). Recent Advances in Non-Thermal Processing Technologies for Enhancing Shelf Life and Improving Food Safety. *Applied*

- Food Research, 3(1), 100258. <https://doi.org/10.1016/j.afres.2022.100258>
- Alsaedi, A. W. M., Al-Hilphy, A. R., Al-Mousawi, A. J., & Gavahian, M. (2024). Non-Thermal Pasteurization of Milk by Elongated Electrode Moderate Electrical Field: Chemical and Sensory Analysis during Cold Storage and Shelf-Life Determination. *Innovative Food Science and Emerging Technologies*, 94, 103647. <https://doi.org/10.1016/j.ifset.2024.103647>
- Alsaedi, A. W. M., Al-Mousawi, A. J., Al-Hilphy, A. R., & Gavahian, M. (2023). Non-Thermal Pasteurization of Milk by an Innovative Energy-Saving Moderate Electrical Field Equipped with Elongated Electrodes and Process Optimization. *Innovative Food Science and Emerging Technologies*, 88, 103445. <https://doi.org/10.1016/j.ifset.2023.103445>
- Anand, A., Kaushal, M., Vaidya, D., Gupta, A., Saini, H. K., & Sharma, R. (2022). Advances in Non-Thermal Technologies in Food Processing: A Review. *Biological Forum – An International Journal*, 14(2), 1419–1428.
- Anjaly, M. G., Prince, M. V., Warriar, A. S., Lal, A. M. N., Kumar, N., Pandiselvam, R., Thirumdas, R., et al. (2022). Ultrasonics Sonochemistry Design Consideration and Modelling Studies of Ultrasound and Ultraviolet Combined Approach for Shelf-Life Enhancement of Pine Apple Juice. *Ultrasonics Sonochemistry*, 90, 106166. <https://doi.org/10.1016/j.ultsonch.2022.106166>
- Astráin-Redín, L., Skipnes, D., Cebrián, G., Álvarez-Lanzarote, I., & Rode, T. M. (2023). Effect of the Application of Ultrasound to Homogenize Milk and the Subsequent Pasteurization by Pulsed Electric Field, High Hydrostatic Pressure, and Microwaves. *Foods*, 12(1457).
- Bahrami, A., Moaddabdoost Baboli, Z., Schimmel, K., Jafari, S. M., & Williams, L. (2020). Efficiency of Novel Processing Technologies for the Control of *Listeria Monocytogenes* in Food Products. *Trends in Food Science and Technology*, 96, 61–78. <https://doi.org/10.1016/j.tifs.2019.12.009>
- Bang, I. H., Kim, Y. E., Lee, S. Y., & Min, S. C. (2020). Microbial Decontamination of Black Peppercorns by Simultaneous Treatment with Cold Plasma and Ultraviolet C. *Innovative Food Science and Emerging Technologies*, 102392. <https://doi.org/10.1016/j.ifset.2020.102392>
- Basak, S., & Chakraborty, S. (2022). The Potential of Nonthermal Techniques to Achieve Enzyme Inactivation in Fruit Products. *Trends in Food Science & Technology*, 123, 114–129. <https://doi.org/10.1016/j.tifs.2022.03.008>
- Bebek Markovinović, A., Stulić, V., Birkić, A., Šaško, D., Ljubičić, J., Kovačević, Z. H., & Kovačević, D. B. (2023). Pulsed Electric Field (PEF) and High-Power Ultrasound (HPU) in the Hurdle Concept for the Preservation of Antioxidant Bioactive Compounds of Strawberry Juice — A Chemometric Evaluation — Part I. *Foods*, 12(3172).
- Bebek Markovinović, A., Stulić, V., Putnik, P., Bekavac, N., Pavlić, B., Milošević, S., Velebit, B., Herceg, Z., & Bursać Kovačević, D. (2024). High-Power Ultrasound (HPU) and Pulsed Electric Field (PEF) in the Hurdle Concept for the Preservation of Antioxidant Bioactive Compounds in Strawberry Juice—A Chemometric Evaluation—Part II. *Foods*, 13(4).
- Beitia, E., Gkogka, E., Chanos, P., Hertel, C., Heinz, V., Valdramidis, V., & Aganovic, K. (2023). Microbial Decontamination Assisted by Ultrasound-Based Processing Technologies in Food and Model Systems: A Review. *Comprehensive Reviews in Food Science and Food Safety*, 22(4), 2802–2849.
- Bigi, F., Maurizzi, E., Quartieri, A., De Leo, R., Gullo, M., & Pulvirenti, A. (2023). Non-Thermal Techniques and the “Hurdle” Approach: How Is Food Technology Evolving? *Trends in Food Science & Technology*, 132, 11–39. <https://doi.org/10.1016/j.tifs.2022.12.015>
- Chakka, A. K., Sriraksha, M. S., & Ravishankar, C. N. (2021). Sustainability of Emerging Green Non-Thermal Technologies in the Food Industry with Food Safety Perspective: A Review. *LWT*, 151, 112140. <https://doi.org/10.1016/j.lwt.2021.112140>
- Chen, F., Zhang, M., Fan, K., & Mujumdar, A. S. (2022). Non-Thermal Technology and Heating Technology for Fresh Food Cooking in the Central Kitchen Processing: A Review. *Food Reviews International*, 38(4), 608–627. <https://doi.org/10.1080/87559129.2020.1740246>
- Chen, T., Li, B., Shu, C., Tian, J., Zhang, Y., Gao, N., Cheng, Z., & Xie, X. (2021). Combined Effect of Thermosonication and High Hydrostatic Pressure on Bioactive Compounds, Microbial Load, and Enzyme Activities of Blueberry Juice. *Food Science and Technology International*, 1–11.
- Clodoveo, M. L. (2019). Industrial Ultrasound Applications in the Extra-Virgin Olive Oil Extraction Process: History, Approaches, and Key Questions. *Foods*, 8(4). <https://doi.org/10.3390/foods8040144>
- Corrêa, T. Q., Blanco, K. C., Garcia, É. B., Perez, S. M. L., Chianfrone, D. J., Morais, V. S., & Bagnato, V. S. (2020). Effects of Ultraviolet Light and Curcumin-Mediated Photodynamic Inactivation on Microbiological Food Safety: A Study in Meat and Fruit. *Photodiagnosis and Photodynamic Therapy*, 30, 101678. <https://doi.org/10.1016/j.pdpdt.2020.101678>
- Deng, L. Z., Mujumdar, A. S., Pan, Z., Vidyarthi, S. K., Xu, J., Zielinska, M., & Xiao, H. W. (2020). Emerging Chemical and Physical Disinfection Technologies of Fruits and Vegetables: A Comprehensive Review. *Critical Reviews in Food Science and Nutrition*, 60, no. 15: 2481–2508. <https://doi.org/10.1080/10408398.2019.1649633>
- Dogu-Baykut, E., & Gunes, G. (2022). Effect of Ultraviolet (Uv-C) Light and Gaseous Ozone on Microbial and Color Qualities of Whole Black Pepper Seeds (*Piper Nigrum* L.). *Carpathian Journal of Food Science and Technology*, 14(2), 122–131.
- Gomez-Gomez, A., Fuente, E. B., Gallegos, C., Garcia-Perez, J. V., & Benedito, J. (2021). Combined Pulsed Electric Field and High-Power Ultrasound Treatments for Microbial Inactivation in Oil-in-Water Emulsions. *Food Control*, 130, 108348. <https://doi.org/10.1016/j.foodcont.2021.108348>
- Grillo, G., Boffa, L., Gaudino, E. C., Binello, A., Rego, D., Pereira, M., Mart, M., & Cravotto, G. (2022). Combined Ultrasound and Pulsed Electric Fields in Continuous-Flow Industrial Olive-Oil Production. *Foods*, 2022. <https://doi.org/10.3390/foods11213419>
- Hales, B. R., Walsh, M. K., & Bastarrachea, L. J. (2022). Synergistic Effect of High-Intensity Ultrasound, UV-A Light, and Natural

- Preservatives on Microbial Inactivation in Milk. *Journal of Food Processing and Preservation*, 1–9.
- Harikrishnan, M. P., Vishnu, V., Kothakota, A., Pandiselvam, R., Pillai, S., Manikantan, M. R., Vishnu, V., Kothakota, A., & Pandiselvam, R. (2023). Impact of Integrated Ultra Violet-Ozone Treatment on Textural and Structural Properties of Dough Made of Natural Fiber Based Agro Residues Impact of Integrated Ultra Violet-Ozone Treatment on Textural and Structural Properties of Dough Made of Natural Fib. *Journal of Natural Fibers*, 20(1), <https://doi.org/10.1080/15440478.2022.2161690>
- Hossain, M. B., Aguiló-Aguayo, I., Lyng, J. G., Brunton, N. P., & Rai, D. K. (2014). Effect of Pulsed Electric Field and Pulsed Light Pre-Treatment on the Extraction of Steroidal Alkaloids from Potato Peels. *Innovative Food Science and Emerging Technologies*, 29, 9–14. <http://dx.doi.org/10.1016/j.ifset.2014.10.014>
- Hwang, H., Lee, J., Min, S. C., & Chung, M. (2023). Application of Intense Pulsed Light – Plasma – Ultraviolet Combined System on Granular and Powdered Foods for Microbial Inactivation. *LWT*, 174, 114447. <https://doi.org/10.1016/j.lwt.2023.114447>
- Jadhav, H. B., Annapure, U. S., & Deshmukh, R. R. (2021). Non-Thermal Technologies for Food Processing. *Frontiers in Nutrition*, 8, 1–14. <https://doi.org/10.3389/fnut.2021.705722>
- Jayasena, D. D., Kang, T., Wijayasekara, K. N., & Jo, C. (2023). Innovative Application of Cold Plasma Technology in Meat and Its Products. *Food Science of Animal Resources*, 43(6), 1087–1110. <https://doi.org/10.5851/kosfa.2023.e88>
- Johnson, O., Sun, D., Cheng, J., & Li, J. (2022). Evaluation of Storage Quality of Vacuum-Packaged Silver Pomfret (*Pampus Argenteus*) Treated with Combined Ultrasound and Plasma Functionalized Liquids Hurdle Technology. *Food Chemistry*, 391, 133237. <https://doi.org/10.1016/j.foodchem.2022.133237>
- Johnson, O., Sun, D., Cheng, J., & Wang, H. (2022). Functional and Bioactive Properties of Larimichthys Polyactis Protein Hydrolysates as Influenced by Plasma Functionalized Water-Ultrasound Hybrid Treatments and Enzyme Types. *Ultrasonics Sonochemistry*, 86, 106023. <https://doi.org/10.1016/j.ultsonch.2022.106023>
- Jones, J. G., Korir, R. C., Walter, T. L., & Everts, K. L. (2020). Reducing Chlorothalonil Use in Fungicide Spray Programs for Powdery Mildew, Anthracnose, and Gummy Stem Blight in Melons. *Plant Disease*, 104(12), 3213–3220. <https://doi.org/10.1094/PDIS-04-20-0855-RE>
- Kaavya, R., Pandiselvam, R., Abdullah, S., Sruthi, N. U., Jayanath, Y., Ashokkumar, C., Khanashyam, A. C., Kothakota, A., & Ramesh, S. V. (2021). Emerging Non-Thermal Technologies for Decontamination of Salmonella in Food. *Trends in Food Science and Technology*, 112, 400–418. <https://doi.org/10.1016/j.tifs.2021.04.011>
- Katsimichas, A., G. Dimopoulos, E. Dermesonlouoglou, and P. Taoukis. 2023. Modelling and Evaluation of the Effect of Pulsed Electric Fields and High Pressure Processing Conditions on the Quality Parameters of Osmotically Dehydrated Tomatoes. *Applied Sciences*, 13(20), 11397
- Khan, I., Tango, C. N., Miskeen, S., Lee, B. H., & Oh, D. H. (2017). Hurdle Technology: A Novel Approach for Enhanced Food Quality and Safety – A Review. *Food Control*, 73, 1426–1444. <https://doi.org/10.1016/j.foodcont.2016.10.046>
- Khezerlou, A., Zolfaghari, H., Forghani, S., Abedi-Firoozjah, R., Alizadeh Sani, M., Negahdari, B., Jalalvand, M., Ehsani, A., & McClements, D. J. (2023). Combining Non-Thermal Processing Techniques with Edible Coating Materials: An Innovative Approach to Food Preservation. *Coatings*, 13(5), 1–19. <https://doi.org/10.3390/coatings13050697>
- Kulawik, P., Rathod, N. B., Ozogul, Y., & Ozogul, F. (2022). Recent Developments in the Use of Cold Plasma, High Hydrostatic Pressure, and Pulsed Electric Fields on Microorganisms and Viruses in Seafood. *Critical Reviews in Food Science and Nutrition*, 1–15. <https://doi.org/10.1080/10408398.2022.2077298>
- Lara, S., Jose, D., Salvador, V., & Blanco, C. (2022). Optical Technologies for Antibacterial Control of Fresh Meat on Display. *LWT*, 160, 113213. <https://doi.org/10.1016/j.lwt.2022.113213>
- Leal Vieira Cubas, A., Medeiros Machado, M., Bianchet, R. T., da Costa Hermann, K. A., Bork, J. A., Debacher, N. A., Lins, E. F., Maraschin, M., Sousa Coelho, D., & Siegel Moecke, E. H. (2020). Oil Extraction from Spent Coffee Grounds Assisted by Non-Thermal Plasma. *Separation and Purification Technology*, 250, 117171. <https://doi.org/10.1016/j.seppur.2020.117171>
- Lee, S. Y., Lee, W. K., Lee, J. W., Chung, M., Oh, S., Shin, J., & Min, S. C. (2021). Microbial Decontamination of Rice Germ Using a Large-Scale Plasma Jet-Pulsed Light-Ultraviolet-C Integrated Treatment System. *Food and Bioprocess Technology*, 542–553. <https://doi.org/10.1007/s11947-021-02590-6>
- Li, X., Li, J., Wang, R., Rahaman, A., Zeng, X., & Brennan, C. S. (2021). Combined Effects of Pulsed Electric Field and Ultrasound Pretreatments on Mass Transfer and Quality of Mushrooms. *LWT*, 150, 112008. <https://doi.org/10.1016/j.lwt.2021.112008>
- Ling, Y., Tan, H., Shen, L., Wei, L., Xiong, G., Wang, L., & Wu, W. (2022). Microbial Evaluation of Ozone Water Combined with Ultrasound Cleaning on Crayfish (*Procambarus Clarkii*). *Foods*, 11, 2314. <https://doi.org/10.3390/foods11152314>
- Ling, Y., Zhou, M., Qiao, Y., Xiong, G., & Wei, L. (2022). Effects of Ozone Water Combined With Ultra-High Pressure on Quality and Microorganism of Catfish Fillets (*Lctalurus Punctatus*) During Refrigeration. *Frontiers in Nutrition*, 9, 1–11
- Mahmoud, M. Z., Fagiry, M. A., Davidson, R., & Kamal, W. (2022). The Benefits, Drawbacks, and Potential Future Challenges of the Most Commonly Used Ultrasound-Based Hurdle Combinations Technologies in Food Preservation. *Journal of Radiation Research and Applied Sciences*, 15(1), 206–212. <https://doi.org/10.1016/j.jrras.2022.03.006>
- Manzoor, M. F., Ahmed, Z., Ahmad, N., Karrar, E., Rehman, A., Muhammad, R., & Ammar, A. (2021). Probing the Combined Impact of Pulsed Electric Field and Sonication on the Quality of Spinach Juice. *Journal of Food Processing and Preservation*, 1–11. <https://doi.org/10.1111/jfpp.15475>
- Manzoor, M. F., Zeng, X., & Rahaman, A. (2019). Combined Impact of Pulsed Electric Field and Ultrasound on Bioactive Compounds and FT-IR Analysis of Almond Extract. *Journal of Food Science and Technology*, 56(5), 2355–2364. <https://doi.org/10.1007/s13197-019-03627-7>
- Mayookha, V. P., Pandiselvam, R., Kothakota, A., Ishwarya, S. P., Chandra, A., Kutlu, N., Rifna, E. J., Kumar, M., Panesar, P. S., & El-maksoud, A. A. A. (2023). Ozone and Cold Plasma: Emerging

- Oxidation Technologies for Inactivation of Enzymes in Fruits, Vegetables, and Fruit Juices. *Food Control*, 144, 109399. <https://doi.org/10.1016/j.foodcont.2022.109399>
- Mehraj, F., Ahmad, Z. R. A., Ahmad, N., & Gul, K. (2023). Recent Advances in Non-Thermal Processing Technologies for Enhancing Shelf Life and Improving Food Safety. *Applied Food Research*, 3(1), 100258. <https://doi.org/10.1016/j.afres.2022.100258>
- Mello, R. E., Fontana, A., Mulet, A., Luiz, J., Corr, G., & Juan, A. C. (2021). PEF as Pretreatment to Ultrasound-Assisted Convective Drying: Influence on Quality Parameters of Orange Peel. *Innovative Food Science and Emerging Technologies*, 72, 102753. <https://doi.org/10.1016/j.ifset.2021.102753>
- Moretti, Alessandro & Gover, Elisabetta & Bisson, Giulia & Comuzzi, Clara & Goi, Daniele & Marino, Marilena. (2023). Kinetic Modeling and Cost-Effectiveness of Salmonella Enteritidis, Escherichia Coli, Enterococcus Spp., and Pseudomonas Spp. Inactivation in Wastewater by Combined Ultrasound-Ozone Advanced Oxidation Processes. <https://doi.org/10.2139/ssrn.4563057>
- Ntourtoglou, G., Drosou, F., Chatzimitakos, T., Athanasiadis, V., Bozinou, E., Dourtoglou, V.G., Elhakem, A., Sami, R., Ashour, A.A., & Shafie, A. (2022). Combination of Pulsed Electric Field and Ultrasound in the Extraction of Polyphenols and Volatile Compounds from Grape Stems. *Applied Science*, 12, 6219. <https://doi.org/10.3390/app12126219>
- Obileke, K., Hart, A., Onyeaka, H., Al-Najjar, S., & Anumudu, C. (2022). Recent Advances in Radio Frequency, Pulsed Light, and Cold Plasma Technologies for Food Safety. *Journal of Food Processing and Engineering*, 1–25.
- Pal, M., Shimelis, A., Mamo, W., Barot, A. M., Pinto, S. V., & Prajapati, J. P. (2017). Hurdle Technology: A Novel Approach for Food Preservation. *Beverage & Food World*, 44(1).
- Pandiselvam, R., Aydar, A. Y., Kutlu, N., Aslam, R., Sahni, P., Mitharwal, S., Gavahian, M., et al. (2023). Individual and Interactive Effect of Ultrasound Pre-Treatment on Drying Kinetics and Biochemical Qualities of Food: A Critical Review. *Ultrasonics Sonochemistry*, 92.
- Patel, Y.K., & Patel, K.K. (2023). High Pressure Processing: An Overview. In A.P. Chhikara & G.C. Navnidhi (Eds.), *Novel Technologies in Food Science* (pp. 479–509). Scrivener Publishing LLC.
- Praeger, U., Herppich, W.B., & Hassenberg, K. (2018). Aqueous Chlorine Dioxide Treatment of Horticultural Produce: Effects on Microbial Safety and Produce Quality—A Review. *Critical Reviews in Food Science and Nutrition*, 58(2), 318–333. <https://doi.org/10.1080/10408398.2017.1317044>
- Ostermeier, R., Hill, K., Dingis, A., Topfl, A., & J., H. (2020). Influence of Pulsed Electric Field (PEF) and Ultrasound Treatment on the Frying Behavior and Quality of Potato Chips. *Innovative Food Science and Emerging Technologies*.
- Rathod, N., Kulawik, P., Özogul, Y., Ozogul, F., & Bekhit, A. (2022). Recent Developments in Non-Thermal Processing for Seafood and Seafood Products: Cold Plasma, Pulsed Electric Field and High Hydrostatic Pressure. *International Journal of Food Science and Technology*, 57, 774–790. <https://doi.org/10.1111/ijfs.15799>
- Rifna, E. J., Singh, S. K., Chakraborty, S., & Dwivedi, M. (2019). Effect of Thermal and Non-Thermal Techniques for Microbial Safety in Food Powder: Recent Advances. *Food Research International*, 126, 108654. <https://doi.org/10.1016/j.foodres.2019.108654>
- Roobab, U., Chacha, J. S., Abida, A., Rashid, S., Madni, G. M., Lorenzo, J. M., Zeng, X. A., & Aadil, R. M. (2022). Emerging Trends for Nonthermal Decontamination of Raw and Processed Meat: Ozonation, High-Hydrostatic Pressure and Cold Plasma. *Foods*, 11(15).
- Sahoo, P., & Chakraborty, S. (2023). Influence of Pulsed Light, Ultrasound, and Series Treatments on Quality Attributes, Pectin Methyl Esterase, and Native Flora Inactivation in Sweet Orange Juice (Citrus Sinensis L. Osbeck). *Food and Bioprocess Technology*, 0123456789. <https://doi.org/10.1007/s11947-023-03042-z>
- Shiekh, K.A., Zhou, P., & Benjakul, S. (2021). Combined Effects of Pulsed Electric Field, Chamuang Leaf Extract and Cold Plasma on Quality and Shelf-Life of Litopenaeus Vannamei. *Food Bioscience*, 41, 100975. <https://doi.org/10.1016/j.fbio.2021.100975>
- Singla, M., & Sit, N. (2021). Ultrasonics Sonochemistry Application of Ultrasound in Combination with Other Technologies in Food Processing: A Review. *Ultrasonics Sonochemistry*, 73, 105506. <https://doi.org/10.1016/j.ultsonch.2021.105506>
- Stepišnik Perdih, T., Zupanc, M., & Dular, M. (2019). Revision of the Mechanisms behind Oil-Water (O/W) Emulsion Preparation by Ultrasound and Cavitation. *Ultrasonics Sonochemistry*, 51, 298–304. <https://doi.org/10.1016/j.ultsonch.2018.10.003>
- Sun, R., Xu, W., Xiong, L., Jiang, N., Xia, J., Zhu, Y., Wang, C., Liu, Q., Ma, Y., & Luo, H. (2023). The Combined Effects of Ultrasound and Plasma-Activated Water on Microbial Inactivation and Quality Attributes of Crayfish during Refrigerated Storage. *Ultrasonics Sonochemistry*, 98, 106517. <https://doi.org/10.1016/j.ultsonch.2023.106517>
- Templalexis, C., Lentzou, D., Samioti, A., & Xanthopoulos, G. (2023). The Individual and Combined Effect of Ozone and UV-C on Mass Loss, Respiration, Texture and Colour Changes of Fresh-Cut Lettuce. *Food Research*, 7(3), 29–41
- Tzima, K., Brunton, N. P., Lyng, J. G., Frontuto, D., & Rai, D. K. (2021). The Effect of Pulsed Electric Field as a Pre-Treatment Step in Ultrasound Assisted Extraction of Phenolic Compounds from Fresh Rosemary and Thyme. *Innovative Food Science and Emerging Technologies*, 69, 102644. <https://doi.org/10.1016/j.ifset.2021.102644>
- Wang, J., & Wu, Z. (2022). Combined Use of Ultrasound-Assisted Washing with in-Package Atmospheric Cold Plasma Processing as a Novel Non-Thermal Hurdle Technology for Ready-to-Eat Blueberry Disinfection. *Ultrasonics Sonochemistry*, 84, 105960. <https://doi.org/10.1016/j.ultsonch.2022.105960>
- Wani, F. A., Rashid, R., Jabeen, A., Brochier, B., Yadav, S., Aijaz, T., Makroo, H. A., & Dar, B. N. (2021). Valorisation of Food Wastes to Produce Natural Pigments Using Non-Thermal Novel Extraction Methods: A Review. *International Journal of Food Science and Technology*, 56(10), 4823–4833. <https://doi.org/10.1111/ijfs.14995>
- Wei, Q., Mei, J., & Xie, J. (2022). Application of Electron Beam Irradiation as a Non-Thermal Technology in Seafood Preservation. *LWT*, 169, 113994. <https://doi.org/10.1016/j.lwt.2022.113994>

- Wiktor, A., Gondek, E., Jakubczyk, E., Dadan, M., Nowacka, M., Rybak, K., & Witrowa-Rajchert, D. (2018). Acoustic and Mechanical Properties of Carrot Tissue Treated by Pulsed Electric Field, Ultrasound and Combination of Both. *Journal of Food Engineering*, 238, 12–21. <https://doi.org/10.1016/j.jfoodeng.2018.06.001>
- Wu, Y., Cheng, J., Keener, K. M., & Sun, D. (2023). Inhibitory Effects of Dielectric Barrier Discharge Cold Plasma on Pathogenic Enzymes and Anthracnose for Mango Postharvest Preservation. *Postharvest Biology and Technology*, 196, 112181. <https://doi.org/10.1016/j.postharvbio.2022.112181>
- Yang, L., Xue, F., & He, D. (2024). Removal of Six Pesticide Residues from Vegetables by the Coupled Ultrasonic-Ozonation Process. *Food Control*, 155, 110109. <https://doi.org/10.1016/j.foodcont.2023.110109>
- Zeraatpisheh, F., Mosallaie, F., Sanaei, F., Falah, F., Vasiee, A., & Yazdi, F.T. (2023). The Simultaneous Influence of Ultraviolet Rays and Cold Plasma on the Physicochemical Attributes and Shelf Life of Dried Pistachios during the Storage Period. *Journal of Food Process Engineering*, 46(9), 1–11.
- Zhang, D., Tang, J., Zhang, G., Wu, X., Sun, Q., Jia, C., Shi, T., et al. (2021). Deposition, Dissipation, Metabolism and Dietary Risk Assessment of Chlorothalonil in Open Field-Planted Cabbage. *Journal of Food Composition and Analysis*, 102, 104008. <https://doi.org/10.1016/j.jfca.2021.104008>
- Zhang, Z., Wang, L., Zeng, X., Han, Z., & Brennan, C. S. (2018). Non-Thermal Technologies and Its Current and Future Application in the Food Industry: A Review. *International Journal of Food Science and Technology*, 1–13.
- Zia, S., Khan, M. R., Shabbir, M. A., Maan, A. A., Khan, M. K. I., Nadeem, M., Khalil, A. A., Din, A., & Aadil, R. M. (2020). An Inclusive Overview of Advanced Thermal and Nonthermal Extraction Techniques for Bioactive Compounds in Food and Food-Related Matrices. *Food Reviews International*, 38(6), 1166–1196. <https://doi.org/10.1080/87559129.2020.1772283>