Sustainable Food Technology

ROYAL SOCIETY OF CHEMISTRY

REVIEW

View Article Online
View Journal | View Issue



Check for updates

Cite this: *Sustainable Food Technol.*, 2025, **3**, 1284

# Advances in non-thermal food processing: a comprehensive approach to nutrient retention, food quality, and safety

Duygu Ağagündüz, [a] Gamze Ayakdaş, [b] Beyza Katırcıoğlu [b] and Fatih Ozogul *[cd]

In recent years, changes in consumer expectations and the requirements for sustainable food production have increased interest in non-thermal processing technologies. Non-thermal food processing technologies have emerged as promising alternatives to traditional methods, offering effective solutions to challenges such as nutrient loss, microbial contamination, and sensory degradation. This article focuses on the effects of six key non-thermal methods, which are high hydrostatic pressure (HHP), pulsed electric field (PEF), ultrasonication (US), cold plasma (CP), ultraviolet irradiation (UV-C), and ozonation on the preservation of heat-sensitive nutrients, food safety, as well as quality parameters. These methodologies will be evaluated, with a discussion of their possible benefits and limits, as well as their applicability in different food systems. Ultimately, this article will contribute to the ongoing discussion about how to optimize food processing techniques for both consumer health and environmental sustainability. Non-thermal technologies can preserve or enhance the bioavailability of heat-sensitive nutrients such as vitamins, minerals, and antioxidants by reducing thermal degradation and improving cellular release. They also offer effective microbial inactivation, notably against common pathogens, through physical or oxidative mechanisms, providing safe and chemical-free disinfection. Additionally, these methods help maintain sensory qualities and improve techno-functional properties while supporting better digestibility, oxidative stability, and shelf life in various food matrices. Moreover, their synergistic combinations offer added value by enhancing antioxidant retention, reducing contaminants, and improving product stability beyond what individual methods achieve alone. With low energy and water consumption, minimal additive use, and support for clean-label production, non-thermal technologies present a comprehensive and sustainable approach to future food systems.

Received 5th April 2025
Accepted 2nd August 2025

DOI: 10.1039/d5fb00136f

rsc.li/susfoodtech

## Sustainability spotlight

Non-thermal food processing techniques make it possible to produce safer, nutritious, and high-quality food by overcoming the shortcomings of traditional methods. Non-thermal food processing techniques provide food safety, quality, and sustainability at the same time, reducing environmental impacts and supporting production processes in line with circular economy principles. With advantages such as saving energy and water, reducing chemical use, and preventing food waste, these technologies have an important place in the sustainable food systems of the future. Moreover, a holistic approach requires a mindset that is not only product-centered but effective throughout the entire supply chain. Energy efficiency, reduction of water consumption, elimination of chemical additives, and reduction of food waste show that these technologies contribute to sustainability goals at a system scale. Therefore, non-thermal technologies are becoming a strategic tool not only for shelf-life and quality optimization but also for the development of climate-friendly, low-carbon-footprint, healthy, and clean-label products. Non-thermal food processing approaches are effective in all processes from micro to macro: preservation of bioactive compounds at the molecular level, functional quality at the product level, efficiency at the process level, and sustainability at the system level. Consequently, for the future of food science and technology, a holistic approach is not just a choice but a strategic breakthrough in food technology. In terms of sustainability, high hydrostatic pressure offers contributions such as low energy and water consumption, no toxic gas emissions, reduced need for chemical preservatives, and no food waste. The importance of pulsed electric field in terms of sustainability is highlighted by its low energy consumption, short processing time, no need for chemical additives, and waste-free processing. In terms of sustainability, ultrasonication is an environmentally friendly technology with its low energy and solvent consumption, non-toxicity, ability to operate at low temperatures, and no need for chemical additives. Owing to these features, it contributes to the development of clean labeled products. At the same time, its ability to achieve many goals, such as extraction, product quality preservation, and yield increase in a single process, makes it stand out among green processing technologies. In freezing processes, the ultrasonication, which reduces the size of ice crystals and preserves cell integrity, minimizes the loss of nutrients while also contributing to environmental sustainability by providing energy savings with

[a]Department of Nutrition and Dietetics, Faculty of Health Sciences, Gazi University, Ankara, 06490, Turkiye
[b]Department of Nutrition and Dietetics, Acıbadem University, Kerem Aydınlar Campus, İstanbul, 34752, Turkiye
[c]Department of Seafood Processing Technology, Faculty of Fisheries, Cukurova University, Adana, Turkiye. E-mail: fozogul@cu.edu.tr
[d]Biotechnology Research and Application Center, Cukurova University, Adana, Turkiye

 

shorter drying times. Cold plasma technology is also very important in terms of sustainability. It is highly energy efficient, reduces the use of chemicals, limits waste generation, and offers an environmentally friendly alternative with low water consumption. It also supports both consumer health and food safety with its efficiency in the degradation of pesticide residues and mycotoxins. The fact that processing with CP technology prevents microbial contamination with minimal damage to product quality, extends shelf life, and reduces waste makes it attractive for sustainable food systems. The sustainability benefits of ozonation are quite strong. It offers an environmentally friendly alternative by reducing the need for chemical disinfectants, reducing water use, leaving no toxic residue, and requiring on-site production.



# 1. Introduction

The processes of access to and consumption of food have changed continuously throughout human history. Since ancient times, humans have developed various methods to store and secure food for longer periods of time. In this process, humans have developed food processing methods to ensure food safety, portability, and nutritional value preservation.[1] Historically, traditional food processing methods such as drying, salting, fermentation, pasteurization, sterilization, and evaporation have been widely used to ensure the microbial safety of food and extend their shelf life.[2] However, these methods can lead to the loss of some bioactive components, especially heat-sensitive vitamins and polyphenols, resulting in a decrease in the nutritional and sensory quality of the food.[3] This underscores the ongoing limitations of thermal processes in preserving delicate micronutrients and bioactives. Recent findings by Ciptaan *et al.* (2024) have highlighted the necessity of exploring gentler alternatives to mitigate such compositional losses.[4] In addition, the effects of climate change on agricultural raw materials are becoming increasingly relevant. Environmental stressors such as rising temperatures and pathogen prevalence can significantly alter the biochemical composition of crops, which may in turn reduce the efficacy of post-harvest processing strategies. Consequently, more resilient and responsive processing methods are required to preserve food integrity in the face of environmental fluctuations.[5]

Consumer demand for minimally processed foods with preserved natural properties and high nutritional value has increased significantly. This trend has driven the development of next-generation techniques that retain the natural profile of foods while ensuring their stability and microbiological safety.[6] In addition, climate change and sustainable production requirements emphasize non-thermal technologies that save energy and do not require chemical additives.[7] Recent paradigms in food systems advocate for preservation-focused, environmentally aligned processing strategies, converging with the rise of functionally enhanced and minimally altered food innovations.[8] Additionally, bioactive-rich compounds like polyphenols have gained attention for their dual role in enhancing microbial control and maintaining organoleptic and compositional integrity.[9]

Non-thermal food processing techniques include innovative methods that aim to extend the microbial safety and shelf life of foods while avoiding the negative effects of heat treatment.[10] These techniques include high hydrostatic pressure (HHP), pulsed electric field (PEF), ultrasonication (US), cold plasma (CP), UV irradiation (UVC), and ozonation.[11]

HHP reduces the microbial load by applying high pressure to foods while preserving heat-sensitive nutritional components to produce fresh-like products.[12] PEF provides microbial inactivation by targeting cell membranes with short-duration high-voltage pulses while preserving sensory properties and nutrients to a great extent.[13] Ultrasonication provides microbial inactivation by disrupting the cell structure with high-frequency sound waves and is used in food processing processes with its effects such as particle size reduction and regulation of enzyme activity.[14] Cold plasma has the advantage of retaining sensory and nutritional quality due to its low-temperature operation, which reduces microbial load *via* reactive species generated by ionized gases.[15] UVC is a method that reduces microbial load on food surfaces and liquid foods using short-wavelength ultraviolet rays. While this technique is mainly used to control surface contamination and eliminate pathogens in liquid foods, it can cause the loss of some photosensitive vitamins depending on the application dose.[16] These methods ensure food safety and quality with shorter processing times and lower temperatures while maintaining fresh-like characteristics of foods with minimal or no change.[11] Ozonation, in contrast, provides microbial inactivation owing to its strong oxidative capacity and stands out as an effective environmentally friendly method to reduce pathogens on water and food surfaces.[17] In this direction, non-thermal food processing techniques make it possible to produce safer, nutritious, and high-quality food by overcoming the shortcomings of traditional methods.[7] Non-thermal food processing techniques provide food safety, quality, and sustainability at the same time, reducing environmental impacts and supporting production processes in line with circular economy principles.[6] With advantages such as saving energy and water, reducing chemical use, and preventing food waste, these technologies have an important place in the sustainable food systems of the future.[18]

This article focusses on the potential of non-thermal food processing techniques by examining comprehensively their impact on nutritional value, nutritional quality, and microbial safety. Innovative techniques including high hydrostatic pressure, pulsed electric field, ultrasonication, cold plasma, UV irradiation, and ozonation will be discussed, and their advantages, limitations, and optimization strategies compared to conventional processing techniques will be evaluated in the light of current scientific findings.

# 2. Recent developments in non-thermal food processing techniques

## 2.1 High hydrostatic pressure

High-pressure processing (HPP), also referred to as ultra-high pressure (UHP) or high hydrostatic pressure (HHP), is a non-thermal method in which food is subjected to uniform pressure from all directions for a short duration. Depending on the food composition, pH, water activity, and microorganism type, it can be achieved bacterial inactivation after application.[19] In HPP, hydrostatic pressure ranging from 100 to 600 MPa is uniformly transmitted throughout the product using a pressure-transmitting medium, and the temperature can be increased up to 60–65 °C.[20] HPP affects non-covalent bonds that are sensitive to pressure. However, small molecules with covalent bonds, such as those responsible for color and bioactive properties, are generally less affected by pressure.[21] Nonetheless, in red meat products, a value—indicating redness—have been shown to significantly decrease following HHP treatment, due to the oxidation of ferrous myoglobin to ferric metmyoglobin and pressure-induced structural changes in proteins. Moreover, this discoloration effect becomes more pronounced as pressure increases from 400 to 600 MPa.[22,23] HHP technology is applied to a wide range of products, such as fruit juices, milk and dairy products, meat and seafood, sauces, vegetable purees, ready-to-eat meals, and baby foods. It is used as an alternative to pasteurization or sterilization, especially in liquid and semi-solid products, and it is preferred to preserve product quality and extend shelf life.[24] In recent years, there has been increasing interest in the use of HHP in milk instead of heat treatment, and its applicability in fermented products, human breast milk, herbal extracts and functional beverages has also been demonstrated.[25] However, HPP cannot be applied to foods with air bubbles, such as bread and cakes, as the structure of these foods may be adversely affected, and to low-moisture foods such as dried fruits due to low microbial inactivation.[24]

Recent studies have shown that HHP is effective not only in microbial inactivation but also in increasing antioxidant capacity, preservation or liberation of bioactive components such as polyphenols, flavonoids as well as vitamins.[26] For example, the extraction of phenolic compounds and antioxidants from tomato waste, red microalgae, grape pulp, and egg yolk has been successfully realized with HHP. Moreover, innovative application areas such as enhancing the bioactive content in fermented beverages and safely processing sensitive matrices like breast milk have gained prominence.[18] In a recent study, HHP pre-treatment of apple juice followed by fermentation with Lactobacillus plantarum significantly enhanced probiotic viability, preserved phenolic compounds, and improved antioxidant capacity compared to thermal pasteurization.[27] Similarly, a broccoli–carrot beverage treated with HHP combined with ultrasound retained high levels of sulforaphane and carotenoids during 28 day storage while achieving ∼6-log microbial reduction, highlighting HHP's compatibility with other non-thermal technologies.[28] The advantages of HHP include preservation of heat-sensitive ingredients, minimal nutrient loss, fresh-like product texture, short processing time, application in packaged products, and eliminating the need for chemical additives.[13,18] It also shows high inactivation efficiency on pathogenic microorganisms, yeasts, and molds.[29] In addition, since HPP causes structural changes in foods, it has been shown that it can be used in the development of foods that provide appropriate textural, color properties, microbiological safety and nutritional values that can be developed specifically for diseases.[30]

However, there are some limitations, such as limited effect on Gram-positive bacteria and spores, insufficient microbial inactivation in low-moisture products, post-treatment tissue changes, as well as high investment cost.[31] In addition, HPP cannot be effectively applied to foods that incorporate air (*e.g.*, bread, sponge cakes), as the presence of air disrupts uniform pressure transmission, leading to structural collapse. Moreover, rigid packaging materials that cannot deform under pressure are unsuitable for HPP, which restricts its application to flexible or semi-rigid packaging systems only.[32,33] HHP has also been shown to effectively inactivate microorganisms and enzymes in solid foods – such as rice bran with 15–77% hydration – only when sufficient water content (aw ≈ 0.95–1.0) is present to ensure uniform pressure transmission; lower moisture levels substantially diminish HPP efficacy.[34]

In terms of sustainability, HHP offers contributions such as low energy and water consumption, no toxic gas emissions, reduced need for chemical preservatives, and no food waste.[18] In these aspects, it is a suitable technology for both environmentally friendly and clean label products.[25,31] Furthermore, the potential of HHP in transforming food processing processes in line with climate change and efficient use of resources is considered important. Thus, HHP technology stands out as one of the food processing technologies of the future, with multifaceted advantages such as maintaining product quality, keeping nutrients stable, ensuring microbial safety, and being compatible with sustainable production principles.[35]

### 2.2 Pulsed electric field

Pulsed electric field (PEF) is a non-thermal processing technology based on the principle of electroporation of cell membranes by applying short-duration and high-voltage electrical pulses to food.[36] This technology changes the structure of microorganisms by making cell membranes more permeable, which kills the microorganisms. Therefore, the shelf life of the product can be extended while nutrients and sensory properties can be largely preserved.[37] Recent studies indicate that PEF systems typically operate with electric field intensities of 15–80 kV cm$^{-1}$ and pulse durations between 0.5 and 100 µs, depending on the food matrix and processing objective.[38–40] For instance, apple juice treated at 35 kV cm$^{-1}$ for 180 µs achieved significant microbial reduction with minimal quality loss;[40] carrot juice exposed to 30 kV cm$^{-1}$ with 45 pulses of 2 µs maintained ascorbic acid and color stability;[41] and orange juice processed at 25 kV cm$^{-1}$ for 100 µs resulted in a 5-log reduction of *E. coli* while preserving vitamin C content.[42] Moreover, milk treated at 18–22 kV cm$^{-1}$ with 1–2 µs pulses showed microbial inactivation without protein denaturation,[43] and aloe vera juice subjected to 20–40 kV cm$^{-1}$ and 50–100 pulses exhibited enhanced polyphenol availability and shelf life.[44] Reversible permeabilization facilitates the release of intracellular components, while irreversible permeabilization leads to cell death.[37] In this context, electroporation is considered the primary mechanism behind the PEF process, where electric field-induced membrane destabilization enables either compound extraction or microbial inactivation, depending on the treatment parameters.[45]

PEF is used for various purposes such as microbial inactivation, enzyme deactivation, extraction efficiency, drying kinetics improvement, and dehydration in liquid or semi-fluid[40] such as milk, fruit juices, potatoes, and seafood.[14] Especially when integrated as a pre-treatment into processes like pressing, osmotic dehydration, convective drying, and freeze drying, it shortens the processing time and reduces the loss of color, aroma, and bioactive components.[26] Notably, synergistic applications of PEF with other non-thermal or mild technologies have gained increasing interest. For example, the combination of PEF-assisted osmotic dehydration and ultrasound enhances mass transfer, reduces water activity, and better preserves phenolic compounds and anthocyanins in strawberries. Similarly, ultrasound-assisted drying after PEF pre-treatment has led to up to 40% shorter drying times with improved retention of color and antioxidant activity in citrus peels.[45,46] In line with these findings, freeze–thaw and low-intensity PEF pretreatments have also been reported to improve drying kinetics and preserve cellular structure in orange peels, particularly when combined with ultrasound-assisted convective drying.[47] These combined effects are attributed to enhanced cell wall disruption and improved diffusivity created by electroporation.[45,46] It is also a preferred technique to increase the bioavailability of bioactive components, such as flavonoids and phenolic content in herbal products.[48] In addition to enhancing the extractability of phenolics, PEF has been shown to affect food structure and texture. For instance, PEF treatment improved tenderness and reduced microbial load in beef by altering protein conformation and increasing sarcoplasmic space, thus contributing to both safety and sensory quality.[49] Similarly, orange juice processed with PEF retained over 85% of its vitamin C content while ensuring microbiological safety through *E. coli* inactivation, demonstrating the balance between preservation and nutritional integrity.[42]

Recent studies have evaluated combinations of PEF with vacuum impregnation, plant extract coatings, and low temperature as part of barrier technology to enhance its microbial inactivation potential.[50,51] It has been reported to be particularly effective in inactivating spoilage microorganisms including *Pseudomonas* and *Enterobacteriaceae* in seafood, reducing oxidative degradation, and suppressing melanosis.[13] However, PEF also has some limitations. Difficulty of application in solid foods, high equipment cost, and factors affecting process stability, such as bubble formation and inhomogeneous area distribution, may limit the widespread use of the technology.[52] In addition, the process parameters need to be carefully optimized, as it does not have the same success in every food matrix.[52,53]

The importance of PEF in terms of sustainability is highlighted by its low-energy consumption, short processing time, no need for chemical additives, and waste-free processing.[48] Besides, it has environmentally friendly advantages, such as reducing pesticide residues and reducing the need for $SO_2$ in wine production.[51] PEF technology is an innovative non-thermal technology that supports the goals of ensuring microbial safety, preserving nutritional components, enhancing bioactive extraction, and sustainable processing. However, process design, equipment suitability, and energy efficiency need to be optimized for wider use at the industrial level.[54,55]

Recent developments in PEF applications highlight its expanding role in postharvest processing, especially for fruit and vegetable preservation. In particular, continuous-flow systems with improved energy efficiency and uniformity are under development to enable large-scale industrial adoption.[38] Moreover, the integration of PEF with enzymatic treatments, hurdle technologies, and natural coating strategies is emerging as a promising route for cleaner-label food processing with enhanced shelf life and functional quality.[56]

### 2.3 Ultrasound

Ultrasound is a non-thermal processing technology based on the application of sound waves with frequencies above the limit of human hearing (>20 kHz) to food systems.[57] According to the frequency and power density used, it is divided into low-intensity US (>100 kHz, <1 W $cm^{-2}$) and high-intensity US (20–100 kHz, >1 W $cm^{-2}$).[58] In the food industry, ultrasound can be applied directly or indirectly through systems like sonotrodes or ultrasonic baths.[59] US is used in many processes such as cutting, cleaning, extraction, emulsification, crystallization, drying, and pasteurization.[60] US inactivates microorganisms by generating cavitation bubbles that collapse near cell membranes, causing physical disruption, membrane damage, and leakage of intracellular components, ultimately leading to cell death.[61] Compared to conventional processes, product loss and energy consumption are lower, and processing time is shorter.[60] US technology contributes to the preservation of the color, aroma, and texture of the product while shortening the processing time, thus minimizing the loss of sensory quality. In addition, it is more successful in preserving vitamins, enzymes, and volatile compounds since it is carried out at low temperatures compared to heat treatments.[62] It is widely used in milk, fruit juices, vegetable juices, alcoholic beverages, fish products, and bakery products in the food industry and has the potential to simultaneously increase process efficiency and product quality.[14,63] US technology enhances homogenization by effectively reducing fat globule size, which leads to improved emulsion stability and viscosity in dairy products.[64] As a pretreatment before hot-air drying, ultrasound accelerates moisture removal by 19–27%, as demonstrated in studies on *Cantharellus cibarius* mushrooms and orange peel, through the formation of microchannels that facilitate water migration while preserving antioxidants and structural integrity.[65] Similarly ultrasound-assisted thin-bed drying has been shown to effectively retain essential nutrients and antioxidant activity in red bell peppers, as it facilitates water migration through the formation of microchannels in the cell wall while preserving antioxidant compounds.[66]

During ultrasonic processes, acoustic cavitation damages cell structures, thereby accelerating mass transfer, reducing particle size, and increasing surface area. As a result of these effects, extraction efficiency increases significantly.[18] Recent studies have shown that ultrasound promotes the preservation and enhanced bioavailability of bioactive components such as phenolic compounds, ascorbic acid, flavonoids, and anthocyanins. Especially in fruit and vegetable juices, including strawberry, mango, pear, carrot, and pomegranate, antioxidant capacity and total phenolic content were increased by US treatment.[14,67] In a recent systematic review, it was concluded that ultrasound treatments exert antimicrobial effects primarily through cavitation-induced mechanical stress, leading to disruption of microbial cell membranes and reduced microbial loads in various food matrices.[68] Recent studies demonstrated that that the application of ultrasound-assisted extraction to fruit peels significantly enhances the yield of polyphenol extracts.[69,70]

Recent developments reveal that ultrasound can be combined with different food processes (enzymatic hydrolysis, membrane filtration, fermentation, *etc.*) to give more effective results, and its multifunctional use is becoming widespread. In addition, in recent years, the use of ultrasound in the extraction of microalgae, grains, and by-products has been increasing, thus enabling the sustainable recovery of valuable components.[18,71] Qian *et al.* demonstrated that the combination of US with organic acids (lactic and citric acids) effectively reduced microbial load and maintained the physicochemical quality of fresh-cut carrots, highlighting the synergistic potential of non-thermal preservation methods.[72] New research has also focused on ultrasound-assisted pH-shift processes to improve protein solubility and emulsification properties, such as in peanut and hemp protein systems, achieving over 2-fold increases in functional performance. Additionally, smart ultrasonic reactors with real-time energy feedback and uniform field distribution have been proposed for industrial scale-up and continuous flow applications.[73]

However, limitations of the technology include the cavitation noise that occurs in ultrasonic processes, possible nutrient losses due to temperature increase, and, in some cases, color changes.[74,75] To increase industrial applicability, careful optimization of process parameters, improvement of equipment design, and homogeneity of energy distribution should be ensured.[76]

In terms of sustainability, US is an environmentally friendly technology with its low-energy and solvent consumption, non-toxicity, ability to operate at low temperatures, and no need for chemical additives. Owing to these features, it contributes to the development of clean labeled products. At the same time, its ability to achieve many goals, such as extraction, product quality preservation, and yield increase in a single process, makes it stand out among green processing technologies.[77] US technology is becoming increasingly important in the food industry in terms of preserving functional ingredients, maintaining product quality, and reducing environmental impacts. However, the proper configuration of technical parameters such as process design and equipment selection is critical for the technology to become more widespread on an industrial scale.[78]

### 2.4 Cold plasma

Cold plasma is a non-thermal processing technology that works by generating reactive oxygen and nitrogen species, free radicals, UV photons, and charged particles through plasma, defined as the fourth state of matter.[3] These ionized gases damage the DNA and protein structures of microorganisms, resulting in microbial inactivation.[79] Since the process is carried out at low temperatures, thermal damage to heat-sensitive foods does not occur, and nutritional quality is largely preserved.[79,80] The primary mechanism involves a dual-phase action: short-lived charged particles and UV photons act at the surface to destabilize microbial cells, while long-lived reactive oxygen and nitrogen species diffuse deeper into the matrix, triggering oxidative and structural alterations in biomolecules such as lipids, proteins, and nucleic acids. The process remains non-thermal due to the nonequilibrium nature of the plasma state, which minimizes heat transfer to the bulk product.[81]

Cold plasma can be generated *via* remote (afterglow), indirect, or direct contact systems such as dielectric barrier discharge (DBD), each differing in the distance between the electrodes and the product, thereby influencing the exposure intensity to reactive species.[82,83] Feed gas composition—commonly He, Ar, $N_2$, $O_2$, or ambient air—determines the spectrum of generated species: oxygen-rich plasmas produce reactive oxygen species (ROS), whereas nitrogen-dominant environments enhance reactive nitrogen species (RNS), both contributing to microbial and chemical decontamination.[81,84,85] Mechanistically, the antimicrobial and functional effects arise from the synergistic action of charged particles, UV photons, ROS/RNS, and electric fields, which disrupt microbial membranes, degrade nucleic acids, and induce oxidative and structural modifications in food matrices.[86,87] Common discharge types employed in food processing include DBD for surface decontamination, atmospheric pressure plasma jets (APPJ) for targeted treatments, and gliding arc or vacuum glow systems for bulk applications.[82,83]

In addition to microbial inactivation in the food industry, cold plasma has versatile applications like mycotoxin degradation, pesticide removal, preservation or enhancement of bioactive components, emulsion stabilization, shortening cooking times, and improving functional properties in some foods.[88] Therefore, it is widely applied in different matrices such as fruits, vegetables, meat, dairy products, and cereals and is considered a promising technology to improve the safety and functionality of food products.[29] Recent studies emphasize that cold plasma can also be used in synergistic approaches. For example, when combined with PEF, it has shown enhanced drying efficiency and polyphenol retention in lychee peel.[89] Similarly, integration of cold plasma with UV-C light has demonstrated synergistic microbial inactivation on fresh-cut produce without compromising texture or color. These synergistic effects are attributed to improved membrane permeability and sequential oxidative stress that amplify inactivation efficiency.[90] Additionally, cold plasma-assisted pretreatment has been shown to induce structural modifications in rice starch, enhancing its complexation with stearic acid and altering functional properties such as thermal stability and retrogradation behavior, thereby offering novel applications for tailored starch-based food systems.[85,91]

Recent advances in CP applications clearly demonstrate the potential of the technology to maintain and enhance the stability of bioactive components. For example, micronutrients such as phenolic compounds, anthocyanins, and vitamin C, and antioxidant capacity have been found to be increased in CP-treated products, and even bioaccessibility in some samples.[92–94] Positive effects on phenolic content and antioxidant activity were reported, especially in products including blueberry, cashew apple juice, orange, and guava. CP has been observed to increase the stability and functionality of components such as ascorbic acid, vitamin E, flavonoids, and phenolic acids. However, it has also been reported that some products may suffer from lipid oxidation, especially at long application times and high voltage levels.[88,95]

CP technology is also very important in terms of sustainability. It is highly energy efficient, reduces the use of chemicals, limits waste generation, and offers an environmentally friendly alternative with low-water consumption.[96] It also supports both consumer health and food safety with its efficiency in the degradation of pesticide residues and mycotoxins. The fact that processing with CP technology prevents microbial contamination with minimal damage to product quality, extends shelf life, and reduces waste makes it attractive for sustainable food systems.[97,98] Moreover, cold plasma's ability to inactivate surface pathogens without water, and its compatibility with clean-label processing, aligns well with circular economy.[99]

However, CP also has some limitations. High initial investment cost, lack of process standardization, the need to carefully optimize application conditions on a product and matrix basis, and quality losses such as discoloration or lipid oxidation that may occur in some products, especially at high voltage levels, are among the major disadvantages.[88,100] There is also a need for further toxicity, safety, and sensory analysis studies for widespread adoption of the technology.[29]

Recent developments in cold plasma technology focus on scaling up continuous-flow plasma systems with optimized gas compositions (*e.g.*, $He/N_2/O_2$) to control the ROS/RNS ratio and improve efficiency across diverse matrices. Advances in nozzle and electrode design, combined with real-time sensors and machine learning algorithms, are also being explored to enhance precision and reproducibility. Emerging applications include cold plasma-assisted seed priming, integration with plant-based edible coatings, and dual treatments with enzymatic or UV-based barriers for maximum microbial safety and minimal sensory alteration.[81,101]

### 2.5 Ultraviolet irradiation

Ultraviolet (UV) irradiation is a non-ionizing, non-thermal food processing method using electromagnetic light in the wavelength range of 100–400 nm. UV-C treatment is typically performed using low-pressure mercury lamps emitting at 254 nm, with system designs ensuring uniform exposure through configurations such as rotating platforms or thin-film flow setups to maximize microbial inactivation efficiency.[16] UV-C wavelength, especially in the 200–280 nm range, prevents the proliferation of microorganisms by triggering the formation of thymine dimers on DNA.[102] Due to this effect, UV-C is often preferred to provide microbial inactivation and improve food safety.[103] UV-C technology has a wide range of applications in the surface sterilization of liquid foods such as fruit juices, dairy products, cider, liquid eggs, honey, beverages, as well as packaging materials, shell eggs, and fresh produce.[104,105] It is also used to reduce surface contamination and extend the shelf life of fresh and fresh-cut fruits and vegetables, lettuces, and blueberries.[104] UV irradiation is a greener alternative to chemical disinfectants, leaving no toxic residues and greatly preserving product quality after treatment.[106]

Recent research shows that UV-C treatment not only provides microbial safety but also increases antioxidant activity in some foods, contributing to the stability of micronutrients such as phenolic compounds and ascorbic acid.[107] For example, UV-C treatments of products such as tomatoes, apples, blueberries, and milk have led to an increase in antioxidant capacity and a reduction in mycotoxins.[104,105,107] It has also been found that in some cases, microbial toxins undergo photocatalytic degradation under UV light, and their toxicity is reduced.[108] UV-C also presents promising synergy when combined with other technologies. For instance, coupling UV-C with ultrasound effectively reduced microbial contamination in cherry tomatoes within a shorter processing time without compromising sensory or nutritional quality.[109] The combination of ultraviolet-C (UV-C) irradiation and HPP effectively reduced aerobic microorganisms as well as yeast and mold populations in "Nanglae" pineapple juice to below detectable levels for 91 days. Compared to conventional thermal processing, this method preserved carotenoids, protein, and ascorbic acid levels to a greater extent while ensuring microbial safety.[110]

The advantages of UV-C technology include low cost, easy installation, energy efficiency, no need to use chemicals, no waste, and minimal damage to the nutritional and sensory qualities of food.[77,105,111] At the same time, UV disinfection of irrigation water provides environmentally friendly sterilization without the use of chemicals such as pesticides or chlorine.[111] The mycotoxin-degrading effect of UV irradiation also provides an important benefit in terms of both environmental health and food safety.[106] Factors such as low-water and energy consumption in UV processes, no toxic waste production, and no residue after disinfection bring UV technology to the forefront among sustainable food processing methods. As an alternative to chemical disinfectants used during food processing, UV-C contributes to both economic and environmental sustainability goals.[104]

However, UV-C irradiation has some limitations. In particular, de low-penetration depth, limited efficacy on inhomogeneous surfaces, and adverse effects like color, taste, or structure degradation can be observed at high doses.[77] In addition, lipid oxidation, vitamin loss, and cellular changes due to photoreactivity may occur. The effectiveness of UV applications varies depending on the surface structure of the product, irradiation dose, duration, application method, and the type of microorganism.[111] Therefore, it is recommended to use UV irradiation in combination with other methods, especially on products with irregular surfaces.[104] UV-C irradiation is a promising, environmentally friendly technology for surface decontamination of liquid and solid foods, ensuring microbial safety, supporting antioxidant capacity, and removing some mycotoxins. However, it is an application that requires specific optimization for each product and should be carefully controlled to avoid negative effects on quality.[77]

### 2.6 Ozonation

Ozonation is a chemical decontamination method based on the strong oxidative effect of ozone gas ($O_3$) to inactivate food products by disrupting microbial cell structures.[29] This technology, which can be applied in gas or aqueous form, is used for versatile purposes such as surface sterilization, fruit juice processing, post-harvest fruit and vegetable processing, and degradation of pesticides and mycotoxins.[37]

Ozone has been confirmed to be highly effective in both reducing microbial contamination and removing pesticide residues in studies on fruits, vegetables, cereals, meat products, and packaging surfaces. Approved by the FDA with GRAS (Generally Recognized as Safe) status, this technology stands out as an environmentally friendly alternative as it leaves no toxic residues on food surfaces.[112] In addition, its breaks down into oxygen as a result of the ozonation process offers an advantage in terms of sustainability due to its lack of environmental persistence.[3]

The antimicrobial activity of ozone is based on its strong oxidizing potential, which enables it to react rapidly with microbial cell membranes, proteins, and nucleic acids. Through mechanisms such as ozonolysis and free radical formation, ozone induces lipid peroxidation, enzyme inactivation, and DNA strand breaks, ultimately resulting in microbial cell death. In aqueous systems, secondary ROS further enhance oxidative degradation, making ozonation highly effective in both surface and structural decontamination.[113]

Recent studies show that ozone treatment effectively degrades mycotoxins such as aflatoxin, ochratoxin A, ZEN, DON, and fumonisin in fruits and vegetables and increases antioxidant stability, shelf life, and safety in products such as sugar cane juice, broccoli, rice, peanuts, corn, milk, and fruit juices.[106] At the same time, losses in phenolic compounds, vitamin C, and total flavonoid content in products can occur after ozonation. This change is generally considered a result of oxidative stress.[17] In particular, excessive ozone exposure in citrus juices has been associated with reductions in ascorbic acid and carotenoids, underscoring the importance of dose and exposure time optimization.[113]

Ozone has gained an important place in the food processing industry for disinfection, shelf life extension, equipment sanitization, and pesticide removal due to its broad-spectrum antimicrobial effect and non-toxic, residue-free nature.[114] When used in gaseous form, it can reach hard-to-reach areas of surfaces, while more surface-friendly applications can be made with its water-solubilized form.[115] Moreover, ozone's ability to structurally break down mycotoxins into less toxic compounds increases its potential in food safety.[106] Ozone treatment has also demonstrated strong performance in reducing microbial load on fresh produce such as lettuce, strawberries, and apples when used in bubbling aqueous form, where it penetrates crevices and irregular surfaces effectively. However, exposure conditions must be tightly controlled to minimize oxidation-induced texture softening or color degradation.[113] However, ozonization technology also has some limitations. Since ozone has high reactivity, it can cause loss of flavor, color, and nutritional value in food products when applied at the inappropriate dosage or time.[116] Especially lipid oxidation and ascorbic acid losses have been reported.[107] In addition, safety precautions should be taken during application, and special ventilation systems should be installed for ozone generators, as ozone can harm human health if inhaled.[37]

The sustainability benefits of ozonation are quite strong. It offers an environmentally friendly alternative by reducing the need for chemical disinfectants, reducing water use, leaving no toxic residue, and requiring on-site production.[117] Moreover, it can be used in integrated approaches in combination with other non-thermal methods (*e.g.*, ultrasound, UV, cold plasma) to increase efficiency and maintain product quality.[29] Recent research has emphasized the synergistic use of ozone with other non-thermal technologies such as ultrasound, UV-C, and cold plasma. For instance, ozone-ultrasound combinations have been shown to improve pesticide removal in guava and spinach, likely due to acoustic cavitation enhancing the diffusion of ozone and generation of secondary radicals. Similarly, ozone combined with UV-C or cold plasma has produced enhanced microbial inactivation and improved shelf-life extension, while reducing ozone dosage requirements. These hybrid approaches support more effective, lower-impact processing by leveraging complementary mechanisms of action.[118–120]

In recent years, advanced ozonation systems utilizing nanobubble or microbubble technology have been developed to enhance ozone solubility and mass transfer in aqueous environments. These systems enable more uniform and effective microbial inactivation with reduced gas input and shorter contact times.[121] Furthermore, smart ozonation reactors with real-time sensors and AI-based control algorithms are under development for more precise dosing, minimizing nutrient loss while ensuring safety.[121,122] Ozonation technology is a promising non-thermal processing method in food processing with its high oxidative power, non-toxic residue-free nature, wide application area, and environmental advantages. However, it is important to optimize the appropriate dose, duration, and form for each product and application in order to maintain product quality and to ensure human health.[116,117] Fig. 1 illustrates the fundamental mechanisms underlying various non-thermal food processing methods.

## 3. Effects on nutritional value and bioavailability

### 3.1 Macronutrients

Non-thermal processing methods have the potential to increase the nutritional value and extend the shelf life of food components by preserving their properties to a large extent.[127] Among

 

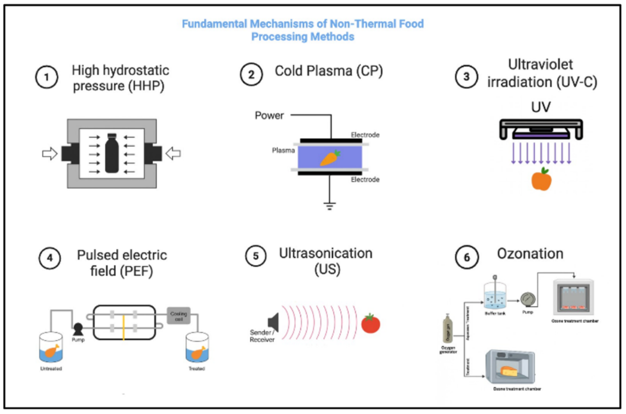


Fig. 1 Fundamental mechanisms of non-thermal food processing methods.[21,81,123–126]

these technologies, HHP treatment has been reported to affect the structural and physicochemical properties of polysaccharides depending on many factors such as molecular size, chemical composition, chain length, application time, and pressure level.[128] Similarly, it is emphasized that the effect of cold plasma treatment varies according to starch-specific properties, including starch chain length, granule size, amylose and amylopectin ratio.[129] Dielectric barrier discharge atmospheric (DBD) and radio-frequency (RF) cold plasma treatment have been shown to increase the thermal stability of amylose by inducing a more ordered helical structure.[130]

In protein structures, HHP-induced conformational changes increase enzymatic hydrolysis susceptibility, leading to smaller molecular weight peptides with potential bioactivities such as antioxidant effects. However, in some cases, protein aggregation through pressure-induced interactions can limit hydrolysis efficiency. Similarly, CP has been shown to alter α-helix and β-sheet structures in plant-based proteins, enhancing solubility, emulsification capacity, and water-holding properties.[107] In terms of lipid components, both HHP and CP applications have contributed to improved oxidative stability, with CP maintaining oil quality in functional lipid sources like flaxseed and walnut oil under optimized parameters.[18] Regarding carbohydrates, HHP has demonstrated enhanced digestibility particularly in slow-digesting and resistant starch fractions[131–134] though some matrices like quinoa have shown contrary results.[135] Non-thermal treatments such as CP and HHP can also help preserve the functional attributes of complex carbohydrates like pectin, leading to nutritional benefits. CP-induced modifications in starch crystallinity and gelatinization temperatures, as well as increased water absorption capacity in treated polysaccharides, positively affect food texture and processability.[136]

PEF technology leads to significant changes in functional and nutritional properties, especially by affecting protein structures. PEF applications can increase the surface hydrophobicity, solubility and emulsification ability of proteins, making them more susceptible to enzymatic digestion. The antioxidant properties of PEF-treated proteins are also improved.[107] Studies in plant and milk proteins show that there are changes in secondary structure (*e.g.* α-helix and β-layer ratios) and these changes directly affect functional properties.[43] In fatty components, PEF appears to drive lipid oxidation processes, and in beverages such as wine and rice wine, some fatty acids can reach natural aging levels. It also has effects on free amino acid profile and can optimize taste profiles.[51]

US technology facilitates the release of macro components (especially proteins, fats, and polysaccharides) from cells through the effect of acoustic cavitation and increases extraction efficiency. In the extraction of vegetable oils, pectins, and proteins, US-assisted methods shorten the processing time and improve solubility and functional properties. The application of ultrasound in proteins leads to the formation of lower molecular weight, high antioxidant potential peptides through the unfolding of structures and the breaking of peptide bonds.[18] Oxidative stability is also maintained in fat components, which enhances the shelf life and functional properties of the fats. Ultrasonically applied Maillard reactions increase both aroma and functional component production; however, the formation of some undesirable products (*e.g.*, HMF) should also be carefully monitored.[76]

Non-thermal treatments are also reported to have remarkable effects on the functional and structural properties of proteins. US, HPP, PEF processes can cause conformational changes in proteins by increasing the sensitivity of protein structures to enzymatic hydrolysis.[137] It has been reported that ultrasound treatment accelerates proteolysis by creating acoustic cavitation and increases the amount of amino acids by playing a role in breaking peptide bonds.[138] In the study conducted by Anema,[139] it was observed that HHP treatment applied in the range of 10–40 °C did not lead to denaturation of α-lactalbumin and bovine serum albumin in skim milk samples; however, increasing temperature and holding time at pressures of 500 MPa and above increased denaturation levels. Liu *et al.* reported that electron beam treatment of egg white proteins improved their functional properties such as solubility, emulsification and gel formation.[140]

CP applications can cause structural and functional changes in macronutrients, affecting the technological and nutritional quality of foods.[3] Especially in legume-based proteins, the use of CP as a pretreatment has promoted the formation of lower molecular weight peptides, making CP a potential technology for the production of bioactive peptides. Additionally, it has been reported that CP causes changes in the α-helix and β-sheet structures, increasing the solubility, emulsification, and water-holding capacities of proteins.[106] In terms of lipids, CP can affect fatty acid profiles through free radicals; it has been noted that oxidative stability can be preserved in functional fat sources with appropriate parameters. In carbohydrate structures, the application of CP reduces starch crystallinity and improves rheological properties by lowering the gelatinization temperature.[18] Additionally, cold atmospheric plasma treatment reduced the antigenicity of the peanut allergen Ara h 1 by 91% by altering its protein structure and amino acid profile; thus, it was evaluated as a potential approach to reduce allergenicity.[141] Ovalbumin (OVA), the main allergen in egg whites, can be reduced in IgG/IgE binding capacity by ultrasound-assisted glycation and PEF processes, enabling safer protein sources to be obtained for allergic individuals.[142] In terms of fat components, non-thermal methods play an important role in maintaining product quality by increasing oxidative stability and have the potential to extend shelf life.[143] For example, cold atmospheric plasma treatment reduced lipid and protein oxidation in mackerel fish and beef meatballs, extending the shelf life of the products and contributing to the preservation of freshness.[144,145] Similarly, irradiation has been reported to reduce lipid oxidation in chicken powdered spices, thereby improving shelf life.[146]

UV-C is a non-thermal technology widely used in microbial inactivation, and it shows limited effects on macronutrients depending on the light dose and application time. In terms of proteins, UV-C can lead to structural changes, particularly through the photooxidation of aromatic amino acids; although mild denaturation has been observed in milk and egg proteins in some studies, it has been reported that the loss of nutritional value is minimal.[111] In lipids, UV-C light can cause oxidative changes such as peroxide formation and flavor deterioration by targeting unsaturated fatty acids, although it has been reported that these effects are limited in samples with high antioxidant content.[106] On carbohydrates, UV-C, particularly in starch, causes slight depolymerization and a decrease in gelatinization temperature; however, it is stated that under appropriate processing conditions, nutritional value and functionality can be largely preserved.[147]

Ozonation is a non-thermal process carried out by applying ozone gas, which has a strong oxidative capacity, to foods, and it shows various effects on macronutrients in addition to microorganism inactivation and pesticide reduction.[112] The effect on proteins is mostly superficial, and it has been reported that it enhances dough quality by promoting the cross-linking of glutenin and gliadin proteins, especially in cereals; however, excessive ozonation has been reported to lead to protein denaturation.[29] In terms of lipids, although there is a potential for oxidative change in unsaturated fatty acids, the oil profile of oily seeds such as hazelnuts and walnuts has been preserved in short-term applications; however, in long-term applications, oxidative stability has been negatively affected due to the increase in peroxide value.[3] On carbohydrates, ozonation causes slight structural disruptions in starch granules and a decrease in gelatinization temperature, while also improving functional properties such as water retention capacity and viscosity, thereby contributing to the processability of food.[148] Table 1 summarizes the effects of this non-thermal processing techniques on the macronutrient content in various food matrices.

### 3.2 Micronutrients

Vitamins and minerals are micronutrients that have regulatory roles in metabolic processes and are essential for human health. Preservation of these elements during food processing is critical for the maintenance of their nutritional value.[151] Conventional heat treatments may lead to the degradation of vitamins, which are particularly sensitive to heat and oxidation, and they may also negatively affect the bioavailability of minerals. At this point, non-thermal processing methods offer the potential to preserve the stability of micronutrients by processing with minimal temperature change, and there have been remarkable developments in this field in recent years.[18]

HHP treatment is one of the prominent methods among non-thermal technologies in terms of preservation and bioavailability of micronutrients. Studies on plant and animal foods have shown that HHP treatment increases the extractability of antioxidant vitamins such as carotenoids, tocopherols, and chlorophyll by disrupting the cell structure.[152,153] At the same time, limited losses were observed, particularly in folate and vitamins C and E, as a result of HHP application, and it was determined that folate can maintain its relative stability under HHP conditions despite its heat-sensitive structure.[154–156] In germinated grain products and rough rice, HHP treatment increased the levels of GABA and vitamins B and E as well as phenolic acids, and this increase was reported to be more

Table 1 Effects of non-thermal processing techniques on macronutrient composition in food products

| Technology | Food/product | Effect | Outcome | Reference |
|---|---|---|---|---|
| HHP | Fermented beverages, human breast milk | Nutrient preservation | Stable immunoglobulins, ↑ antioxidant content | 18 and 25 |
| HHP | Tomato waste, red microalgae, grape pulp, egg yolk | Phenolic & antioxidant extraction | ↑ antioxidant capacity, ↑ polyphenols | 26 |
| HHP | Quinoa | Digestibility changes | ↓ digestibility | 149 |
| PEF | Wine | Stabilization of ascorbic acid | Improved aging, balanced flavor | 51 |
| US | Fermented pumpkins | Bioactivity change | ↑ antioxidant activity after fermentation | 150 |
| US | Wheat flour | Gluten cross-linking | Improved dough quality | 74 |
| CP | Flaxseed, walnut oil | Oxidative stability | Preserved oil quality | 18 |
| CP | Legume-based proteins | Structural transformation | ↑ solubility, ↓ allergenicity | 106 |
| UV-C | Milk, egg proteins | Structural changes *via* photooxidation | Mild denaturation; value mostly preserved | 111 |
| Ozonation | Wheat, cereals | Protein structure modification | ↑ dough quality *via* gluten cross-linking | 29 |
| Ozonation | Wheat flour, nuts | Protein & lipid modifications | ↑ dough quality; some oxidation in lipids | 3 and 29 |
| Ozonation | Starch-containing foods | Carbohydrate structure optimization | ↑ viscosity, ↑ water retention, ↓ gelatinization temp | 148 |

 

pronounced at certain pressure levels.[155,157] In animal-derived foods like milk and eggs, sensitive components such as folate and immunoglobulins were reported to be stable against HHP treatment, while the solubility of minerals such as calcium, phosphorus, and zinc increased due to changes in casein micelles and protein-matrix structures.[152,156,158] In particular, the weakening of folate's bonds with phosvitin has a favorable effect on its bioavailability.[156] However, it is emphasized that HHP treatments combined with the germination process further improve the bioavailability of minerals such as zinc and iron by reducing phytic acid levels and are effective in reducing anti-nutritive factors.[157,159,160] Additionally, it has been stated that HHP changes the mineral distribution and calcium–phosphorus ratio depending on the product matrix. This could cause variations in the nutritional profile of dairy products.[152] The potential of HHP to both maintain nutrient stability and improve bioaccessibility suggests that it is an effective non-thermal technology for the production of functional and fortified foods.[161–163]

In studies conducted with PEF technology, it has been reported that vitamins A, C, and B group vitamins are largely preserved, particularly as ascorbic acid and carotenoids reach higher bioaccessibility after PEF treatment.[164] In fruit and vegetable tissues, PEF pretreatment shows positive effects on the preservation of polyphenols and flavonoids while maintaining the stability of bioactive components such as β-carotene and vitamin C.[164–166] However, some studies have revealed that PEF applied at high energy densities may cause losses in ascorbic acid and polyphenols due to the intensity of the process.[164,167] Molecular analyses on the oxidative stability of vitamin C have shown that PEF promotes the structural transformation of ascorbic acid (enol → keto form), slowing down the oxidation process and increasing its antioxidant capacity. In liquid foods including fruit juice and dairy products, PEF treatment has been reported to better preserve vitamins C and B compared to conventional heat treatments while supporting the sustainability of sensory properties.[168,169] Moreover, the stability of heat-sensitive vitamins such as folate, thiamine, and riboflavin was reported to be high, and the combination of PEF + mild heat provided microbial safety without nutrient loss.[169] Although PEF treatments are generally considered stable in terms of mineral content, electrode-induced increases in Fe concentration have been observed in some cases.[164] However, PEF has also been shown to increase the ion uptake capacity of *Saccharomyces cerevisiae* cells for the biofortification of trace elements such as zinc and selenium.[170] PEF technology is also reported to improve both nutrient content and bioavailability by increasing the extractability of β-carotene and other bioactive compounds in plant-based products.[167] The ability of PEF to be applied at low temperature in a short time makes it an effective non-thermal alternative for preserving micronutrients and improving the functional quality of food.[164–167]

US technology is an effective non-thermal processing method that disintegrates cell walls by cavitation, releasing micronutrients and increasing their bioaccessibility.[171,172] Low-frequency, high-intensity US applications significantly increase the extraction efficiency of bioactive components such as flavonoids, polyphenols, and tocopherols, while maintaining the stability of heat-sensitive vitamins such as ascorbic acid, folate, and carotenoids.[173–175] US treatment minimized the loss of vitamin C in fruit products such as orange, tomato, strawberry, and bergamot juice, while providing positive effects on total phenolic and antioxidant capacity.[173–177] High-power ultrasound treatments promoted vitamin A activity by increasing the solubility of pigments such as lycopene and beta-carotene in tomato and carrot juice and contributed to the preservation of vitamin C and B group vitamins in products such as meat, chicken, and yogurt.[176,178] US technology also increases the bioavailability of minerals such as iron, zinc, calcium, and magnesium and supports their digestibility by allowing them to be released more easily from the food matrix.[179–181] In liquid foods, yogurt, and dairy products, even in frozen and dried foods, ultrasonic treatments are reported to minimize both vitamin and mineral losses.[182] Furthermore, ultrasound technology, combined with processes like drying and freezing, has emerged as a strategic tool to preserve the functional properties of products by reducing the thermal degradation of nutrients.[179]

CP, especially oxidation-sensitive compounds such as vitamin C, folate, and B group vitamins, can be highly protected during CP treatment; in some cases, the stability of these vitamins is increased, and their bioavailability is improved.[79,183,184] CP treatments of vitamin C-rich fruits such as kiwifruit, camu–camu, blueberries, jujube, and anacardium apples preserved the functional properties of the products by limiting the oxidative degradation of ascorbic acid.[183,185–188] Similarly, the oxidative stability of vitamins C and B was maintained in animal-derived foods such as meat, milk, and mushrooms, while protective effects were reported for vitamins A and E in some samples depending on the processing conditions.[79,189–192] Although the effects of CP technology on mineral content are mostly indirect, it has been observed that the solubility and bioavailability of minerals such as iron, zinc, potassium, and magnesium are increased through the degradation of anti-nutrient components such as phytate.[193,194] This procedure facilitates the passage of minerals contained in plant matrices into the digestive tract, strengthening the potential of CP for use in functional food production. However, it is emphasized that CP can also lead to degradation of some vitamins (especially vitamins C and E) through reactive species production, so the treatment time, voltage, frequency, and gas composition should be carefully optimized.[80,195,196] Depending on the product matrix, treatment time, and energy density, differences in vitamin stability and mineral bioavailability may occur. As a result, CP technology is considered an environmentally friendly non-thermal processing alternative that can contribute to the production of functional and nutritious foods by preserving both vitamin and mineral content at high levels when optimized according to the process conditions.[195,197]

It has been demonstrated that UV-C treatment can tend to decrease bioactive components like vitamin C and phenolic compounds.[16,198–200] For example, it was reported that UV-C exposure in apple and kale juice resulted in statistically significant decreases in ascorbic acid levels, with this effect being more pronounced in clarified products.[201] However, in orange, carrot, and celery juice blends, UV-C treatment increased the carotenoid content by up to 84%, indicating that it can support the bioavailability of bioactive compounds under certain conditions.[16,202] In studies on fungi, it has been reported that UV-C light induced a significant increase in vitamin D levels by triggering ergosterol → vitamin $D_2$ conversion.[203] In sensitive matrices including human milk and grapes, UV-C treatment caused limited losses in α-tocopherol levels, while γ-tocopherol and some immune proteins were able to maintain stability.[204,205] It was also emphasized that furan formation caused by UV-C treatment could be reduced by the addition of antioxidants, thus preventing vitamin losses.[198] Findings on mineral content are limited; most studies reported that UV-C does not cause significant changes in minerals or may affect bioavailability through indirect effects.[200,201,206] In general, the effects of UV-C treatment on micronutrients depend on many factors including light transmittance, application time, dose, product matrix structure, and presence of antioxidants.[201]

Ozonation technology draws attention as an effective non-thermal treatment to increase the microbial safety and extend the shelf life of foods owing to its strong oxidative capacity. Its effects on micronutrients vary depending on factors such as product type, application method, and dose. For instance, an increase in ascorbic acid levels was observed in parsley treated with $O_3$-micro–nano bubble water ($O_3$-MNBW), and this effect was associated with increased antioxidant enzyme activities, and nutritional quality was preserved.[207] Long-term studies on *Lonicera* spp. revealed that ozone treatment significantly improved the antioxidant capacity of the fruits by increasing vitamin C and total polyphenol content.[208] Similarly, it was found that 300 ppb of ozone gas applied to ‘Soreli’ kiwifruit promoted ascorbic acid, polyphenol, and flavonoid content and improved microbial quality in samples stored at low temperature.[209] In contrast, it was reported that although ozonated water treatment of apple samples greatly reduced pesticide residues, it caused a loss of up to 83.66% in ascorbic acid content with a treatment time of 30 minutes and caused a decrease in some anthocyanins.[210] These differences suggest that ozone treatment may positively or negatively affect vitamin stability depending on the treatment time, concentration as well as structural characteristics of the product. In general, there is limited data on the direct effects of ozone on mineral content, although some studies suggest that increased antioxidant capacity and enzyme activity may have positive effects on mineral metabolism.[207,211] Table 2 summarizes the effects of this non-thermal processing techniques on the micronutrient content in various food matrices.

### 3.3 Bioactive compounds

Food processing has a direct impact on the bioavailability of bioactive compounds such as antioxidants, vitamin C, glutathione, β-carotene, α-tocopherol as well as various flavonoids.[214] Processes such as deglycosylation of flavonoids as a result of tissue destruction may increase bioavailability by making these compounds more accessible.[214,215] It is reported that these bioactive compounds are preserved at a higher level in foods processed with non-thermal technologies and the anti-diabetic, anti-hypertensive, anti-microbial and anti-cancer potential of these compounds can be revealed more effectively.[216] It is noteworthy that these methods are capable of preserving important nutritional components as well as ensuring microbiological safety in the processing of breast milk, which is considered to be the most suitable food source for newborns.[217,218]

For instance, it was reported that the combination of ultrasound and microwave provides a significant increase in phenolic compounds and flavanols in tangerine juice, while in beetroot sample, batalain content and antioxidant activity are improved by ultrasound-assisted extraction.[138,219] Ultrasonic pre-treatment before thawing has been reported to increase the extraction yield of bioactive compounds[220] and this process was reported to increase phenolic matter and antioxidant activity levels in apples by reducing drying time by 11–15%.[221] Similarly, Zhang *et al.*[222] reported that the bioavailability of micronutrients such as carotenoids, phenolic compounds and ascorbic acid increased significantly after ultrasound pretreatment. Shaik *et al.*,[223] reported that thermal pasteurization of sweet lime juice resulted in a 38.6% and 42.2% reduction in total phenolic content and antioxidant activity, respectively, while sequential pulsed light and ultrasound treatment resulted in lower losses of 4.1% and 3.9%, respectively. Öğüt *et al.*[150] showed that ultrasound technology improved the anticancer properties of wild apple vinegar by preserving and increasing its bioactive components. In contrast, it was reported that the loss of phenolic compounds increased after ultrasound pretreatment in fermented pumpkins after ultrasonic pretreatment, whilst an increase in antioxidant activity was observed after fermentation.[224] Ultrasonic bleaching techniques have been shown to reduce the total tocopherol and sterol content of sunflower oil more than industrial bleaching techniques.[225]

HHP and PEF treatments of ranberrybush fruit were also reported to maintain the bioactivity of phenolic compounds after digestion.[226] HPP and electron beam irradiation (EBI) treatments enhanced the shelf-life stability of fermented spicy Chinese cabbage sauce, improved the extractable contents of total phenolic compounds and carotenoids, and significantly increased its antioxidant capacity.[227] Dao *et al.*[228] showed that HPP treatment increased total phenolic compounds in pigmented rice grass juice by increasing many phytochemical compounds such as protocatechuic acid and quercetin. US combined with HPP treatment at mild temperatures and for short periods of time effectively increased the extraction of bioactive compounds in fig puree and did not adversely affect the volatile compounds of the fruit.[229] According to Jiménez-Pulido *et al.*[230] the combined treatment of hydrolysis and HPP in wheat bran and oat hulls increased phenolic compounds (especially ferulic acid) and β-glucan content and antioxidant activity, and decreased phytic acid content. HPP treatment (600 MPa, 3 min, 4 °C) of sour cherries was shown to preserve the color, total polyphenols and total anthocyanins of the cherries at levels comparable to fresh product over a storage period of 3 months, while providing microbial inactivation.[231]

 

Table 2 Effects of non-thermal processing techniques on micronutrient composition in food products

| Technology | Food/product | Effect | Outcome | Reference |
|---|---|---|---|---|
| HHP | Milk, eggs | Mineral and folate interaction | Folate stable, ↑ Ca, P, Zn solubility | 152, 156 and 158 |
| HHP | Germinated grain products, rough rice | Vitamin and amino acid bioenhancement | ↑ vitamins B, E, phenolic acids, GABA | 155 and 157 |
| PEF | Carrot juice | Carotenoid extractability enhancement | ↑ β-carotene extractability | 167 |
| PEF | Yeast (*Saccharomyces cerevisiae*) | Biofortification *via* mineral uptake | ↑ Zn and Se uptake | 170 |
| PEF | Wine, rice wine | Stabilization of ascorbic acid | ↑ ascorbic acid antioxidant activity | 51 |
| US | Orange, tomato, strawberry, bergamot juice | Vitamin and flavonoid preservation | ↑ vitamin C, ↑ antioxidant capacity | 173, 176 and 177 |
| US | Meat, chicken, yogurt | Vitamin and mineral preservation | ↑ vitamin C & B vitamins, ↑ mineral preservation | 176 and 178 |
| CP | Cherries, kiwis, blueberry juice, mushrooms | Shelf life extension and flavor stability | Reduced microbial load, maintained aroma | 183, 184 and 190 |
| CP | Camu–camu, anacardium apple, blueberries, winter jujubes | Micronutrient stabilization and sensory retention | Preserved vitamin C, potassium, aroma and texture | 185, 186 and 188 |
| CP | Meat, milk, mushrooms | Micronutrient stabilization under CP | ↑ vitamins A, E, C, B stability | 189–192 |
| CP | Meat, meat products | Textural and functional enhancement | ↑ water-holding, improved flavor and color | 189, 191 and 212 |
| CP | Shrimp, seafood | Protein and antioxidant enhancement | ↑ antioxidant activity, stabilized protein | 195 and 213 |
| CP | Coconut milk | Sensory and microbial quality improvement | ↑ aroma, effective microbial inactivation | 196 |
| UV-C | Orange, carrot, celery juice blends | Photochemical enhancement of carotenoids | ↑ carotenoid content | 202 |
| UV-C | Milk, grapes | Photooxidation and tocopherol interaction | Limited α-tocopherol loss, other nutrients stable | 204 and 205 |
| Ozonation | Parsley | Ozone-induced antioxidant enzyme activation | ↑ ascorbic acid *via* antioxidant enzyme activity | 150 |
| Ozonation | Hazelnuts, walnuts | Lipid protection in short-term ozonation | Preserved oil profile; long-term: oxidation risk | 3 and 29 |
| Ozonation | Sugar cane juice, broccoli, rice, peanuts, corn, milk, fruit juices | Mycotoxin degradation and antioxidant protection | ↑ antioxidant stability, ↑ shelf life | 106 |

Cold atmospheric plasma (CAP) treatments showed similarly favorable effects in various fruits. CAP was shown to increase phenolic content in beetroot juice,[232] increase antioxidant activity, vitamin C and phenolic compound concentrations in lime fruit[233] and help preserve bioactive components in banana slices during blanching.[234] Ultrasound-assisted extraction of used coffee grounds after CAP pretreatment significantly increased total phenolic content and antioxidant activity.[235]

PEF is a promising non-thermal technique for the preservation of phenolic components of vegetable and fruit juices[236] urging PEF-assisted extraction, total phenolic content (TPC), flavonoid content (FC), total anthocyanin content (TAC), tannin content (TC) and antioxidant activity (FRAP) values of red grape pomace were improved by 15%, 60%, 23%, 42% and 31%, respectively.[237] The medium intensity PEF (0.25 kV $cm^{-1}$) increased the amount of some bioactive compounds, especially carotenoids with high antioxidant activity (such as radical scavenging activity) in tomato.[238] In extra virgin olive oil, US and US-PEF combined treatments increased its quality and market value by enriching polyphenols (8–12%) and tocols (3–5%).[239] Low-temperature processing with and without high pressure combined with PEF treatment resulted in the highest preservation of the main phenolic compounds content of apple pomace extracts.[240]

UV-C light and ultrasonication treatments enriched most bioactive compounds in hawthorn vinegar and made anticarcinogenic activities more pronounced.[241] Levent and Aktaş revealed that UV light and ultrasound applied before germination increased total phenolic content and antioxidant activity more than black lentil samples germinated without any treatment.[242] UV-A irradiation at 12 W significantly increased anthocyanin, chlorophyll, polyphenol and ascorbic acid accumulation in broccoli and radish sprouts.[243]

While ozone technology is an effective sterilization technique and is known to stimulate the synthesis of bioactive and antioxidant compounds by activating secondary metabolic pathways, there are conflicting results in the literature.[244] It was reported that ozone processing, especially 2 ppm/9 minute and

5 ppm/3 minute applications, preserved the physicochemical properties, bioactive compounds and visual appearance of fresh plums during storage.[245] On the contrary, when ultrasonication and ozone treatment of candied apple juice were compared, it was reported that ultrasonication increased the preservation of bioactive compounds, but ozone treatment showed detrimental effects by reducing TPC, vitamin C and flavonoid content.[246] Ozone processing induced microbial inactivation in watermelon juice but caused significant changes in some physicochemical properties and significant degradation of bioactive compounds.[247] Ozone treatment of *Lonicera caerulea* L. fruits was found to significantly increase their antioxidant value.[248] Table 3 summarizes the effects of the non-thermal processing techniques on the bioactive compounds in various food matrices.

## 4 Effects on food quality

HHP technology offers significant advantages in terms of preserving and improving nutritional quality while ensuring the microbial safety of foods. In fruit and vegetable-based products including plum puree, red pepper puree, melon, and grapefruit juices, HHP contributed to the preservation or enhancement of bioactive components like vitamin C, polyphenols, and total antioxidant activity, with minimal changes in physicochemical properties such as color, pH, and soluble solids.[18,26,31] Similarly, in products like aronia, strawberry-apple-lemon, and broccoli-carrot mixture, HHP treatment was shown to maintain color stability, antioxidant capacity, and sensory quality better than heat treatments and significantly reduced microbial load during storage.[28,250,251] The ability of HHP to modify protein structure has improved parameters such as emulsion stability and viscosity in dairy products and supported textural quality aspects including gel formation aa well as texture improvement in meat products.[252] In addition, it can reduce the glycemic response by facilitating gelatinization in foods with high starch content and preserve taste and shelf life in low-salt formulations, allowing the development of healthier meat products.[162] HHP also provides functionality in terms of protein digestibility; for example, it contributes to the formation of functional peptides by increasing the digestibility of β-phosvitin protein in egg yolk granules.[253] All these findings indicate that HHP can better preserve sensory, physicochemical, and functional quality in different food matrices compared to thermal treatments and therefore is an effective technology in cold chain processes.[18,26,31]

Table 3 Effects of non-thermal processing techniques on bioactive compounds in food products

| Technology | Food/product | Effect | Outcome | Reference |
|---|---|---|---|---|
| HHP | Pigmented rice grass juice | Flavonoid and antioxidant synthesis stimulation | ↑ quercetin, phenolics | 229 |
| HHP | Tomato waste, grape pulp, red microalgae | Phenolic and antioxidant liberation *via* HHP | ↑ antioxidant peptides, polyphenols | 26 |
| PEF | Red grape pomace | Cell disruption and anthocyanin extraction | ↑ anthocyanins, ↑ phenolics | 238 |
| PEF | Tomato | Electroporation-induced antioxidant increase | ↑ carotenoids, ↑ antioxidant compounds | 239 |
| US | Beetroot | Betalain enrichment and antioxidant activation | ↑ betalains, ↑ antioxidant capacity | 249 |
| US | Apple | Phenolic compound retention | ↑ phenolics, ↑ antioxidant activity | 221 |
| US | Wild apple vinegar | Preservation of anticancer phytochemicals | ↑ anticancer bioactives | 224 |
| US | Hawthorn vinegar | Ultrasound-induced enrichment of bioactives | ↑ bioactive compounds, ↑ anticancer potential | 242 |
| US | Black lentil (germinated) | Ultrasound-enhanced sprouting | ↑ total phenolics, ↑ antioxidant activity | 243 |
| US | Candied apple juice | Preservation of bioactive compounds | ↑ bioactive retention compared to ozone | 247 |
| CP | Blueberries | Phenolic compound stabilization | ↑ phenolics, ↑ antioxidant stabilization | 188 |
| CP | Beetroot juice | Ultrastructural change enabling antioxidant release | ↑ phenolics, ↑ antioxidant capacity | 233 |
| UV-C | Cherry tomatoes | UV-C triggered antioxidant accumulation | ↑ lycopene (up to 6-fold) | 17 |
| Ozonation | Juniper berries | UV-C triggered antioxidant accumulation | ↑ total phenolics | 17 |
| Ozonation | Kiwifruit | Ozone-stimulated phenolic synthesis | ↑ vitamin C, ↑ phenolics | 209 |
| Ozonation | Candied apple juice | Oxidative degradation under ozone exposure | ↓ TPC, ↓ vitamin C, ↓ flavonoids | 247 |
| Ozonation | Watermelon juice | Bioactive compound degradation | Significant degradation of bioactive compounds | 248 |
| Ozonation | *Lonicera caerulea* L. fruits | Ozone-enhanced antioxidant bioactivity | ↑ antioxidant value | 208 |

 

PEF technology has contributed to the preservation of visual and structural quality by providing significant reductions in ΔE and the index of cell structure damage in carrots.[165] Similarly, PEF-assisted drying applications have shown positive effects on β-carotene, antioxidant capacity, and color parameters in products such as apricots and pumpkins; significant reductions in processing time and energy consumption have been achieved.[254] PEF pretreatments have also increased oil yield by up to 17% in olive oil extraction, enhanced the levels of antioxidant components, and significantly preserved product quality.[255,256] In applications involving pomegranate juice, coconut water, and dairy products, it has been noted that physicochemical parameters including pH, °brix, and viscosity remained stable, while increases in vitamin C and phenolic content were achieved, and enzymatic degradation was reduced through the inactivation of PPO and POD.[257–259] In meat products, PEF has caused positive changes in quality determinants like water-holding capacity, tissue stability, and free amino acid profile by shortening the dissolution time.[260,261] In addition, it has been stated that PEF changes functional properties like viscosity, foam stability, and emulsifying capacity depending on voltage and duration in egg products. In dairy products, it kills microorganisms when mixed with low temperature while keeping nutritional components. In plant products such as spinach and potatoes treated with PEF, it has also been reported that cellular integrity is preserved and undesirable compounds like acrylamide formation can be reduced.[262,263] Finally, studies have reported that PEF shortens the fermentation time, diminishes syneresis, and enhances the firmness of yogurt products fermented with starter cultures.[264]

High-power ultrasound applications reduce particle size in processes such as emulsification and homogenization, thereby enhancing the stability and textural quality of products, resulting in more homogeneous structures and improved viscosity properties in dairy products.[171,265] Additionally, US reduces microbial load, extending shelf life and preserving the sensory qualities of food, such as taste, aroma, and color, by maintaining its organoleptic properties.[173,266–268] US treatments applied to fruit- and vegetable-based products like baobab, amla, and carrot enhance the bioavailability of phenolic compounds and inhibit spoilage enzymes like polyphenol oxidase and peroxidase, thereby maintaining color stability.[174,268,269] Ultrasound-assisted osmotic dehydration improves the microstructure of the product while enhancing tissue integrity, thereby increasing both visual and textural quality.[270] US application also enhances the water retention capacity and tenderness of meat and poultry products by inducing protein denaturation and structural transformation, supports microbial safety, and extends shelf life.[172,177,178] In freezing processes, the US, which reduces the size of ice crystals and preserves cell integrity, minimizes the loss of nutrients while also contributing to environmental sustainability by providing energy savings with shorter drying times.[182,271] In liquid foods, both microbiological safety and overall product quality are improved through the more effective extraction of aroma compounds, color preservation, and the stabilization of biologically active components.[180,272] Next-generation approaches like sonoprocessing and direct contact ultrasound (DTU) aim to preserve food components and optimize nutritional values, making US technology a strong non-thermal alternative in terms of both functional and sensory quality.[273,274] Improvements in viscosity, color, and taste parameters have been reported in products such as yogurt and carrot juice; this is a significant effect that increases consumer preference.[275,276]

CP technology has been found to be particularly successful in preserving sensitive micronutrients including vitamin C and potassium in fruit-based products like camu–camu,[185] Anacardium apple,[186] blueberries,[188] and winter jujubes;[277] positive effects have also been observed on organoleptic properties like aroma, texture, and color. CP has been reported to reduce microbial load, extend shelf life, and maintain the stability of flavor and aroma compounds in products such as cherries,[278] kiwis,[183] blueberry juice,[184] and mushrooms.[190] In meat and meat products, CP applications enhance the flavor profile by allowing the release of aroma compounds while improving parameters like texture, color, and water-holding capacity, thereby increasing product quality.[189,191,212] Especially in high-protein foods including shrimp[195] and seafood,[213] CP can enhance sensory quality while maintaining protein stability and increasing antioxidant activity. However, CP applications can sometimes trigger lipid oxidation, leading to the formation of undesirable compounds such as aldehydes and carboxylic acids, which can negatively affect taste and nutritional value.[192] Disturbances in properties such as color, texture, and aroma have been reported in DBD-CAP (dielectric barrier discharge atmospheric cold plasma) systems when process parameters (duration, voltage, gas type) are not optimized.[80,279] It has been noted that SP applications can cause color changes in some leafy green vegetables through pigment oxidation and that there may be reductions in bioactive components like vitamin C, phenolic compounds, and chlorophyll. Nevertheless, the literature also highlights the positive effects of CP technology, such as its capacity to remove chemical contaminants like pesticides, its ability to enhance antioxidant capacity by increasing the release of natural compounds, and its modulation of protein functionality through enzymatic processes.[280,281] Additionally, in liquid products such as coconut milk, CP contributes to the preservation of sensory quality by promoting the formation of aroma components while providing microbial inactivation.[196] Overall, CP is a versatile technology that supports the nutritional value and physicochemical quality of both fruits and vegetables as well as animal products; however, it is necessary to carefully optimize the application parameters, conduct product-based evaluations, and minimize potential negative effects.[282]

UV-C light is one of the non-thermal technologies that has the potential to extend the shelf life of foods by reducing microbial contamination. The application can provide microbial inactivation in various foods while largely preserving the physicochemical and nutritional value of the products.[16,204] For instance, processes performed on human milk using UV-C light have better preserved bioactive proteins and enzymes including IgA, lactoferrin, lipase, and lysozyme compared to Holder pasteurization, and no increase in lipid oxidation products has been observed.[204] In addition, it has been reported that the addition of antioxidants can reduce the formation of UV-C-derived furan, thereby contributing to chemical safety.[198] UV-C irradiation can support the production of plant-based vitamin D by converting provitamin D into its active form in some fruit and vegetable products.[283] In studies conducted on mango juice, the combination of UV-C and sonication increased the extraction of carotenoids, polyphenols, and flavonoids, enhanced antioxidant capacity, and extended shelf life by reducing microbial load.[107] Similarly, it has been reported that UV-C treatment increased the lycopene content in cherry tomatoes by up to six times and significantly improved their quality.[17] In studies conducted on kale juice, grape juice, and other vegetable-fruit juices, it has been noted that the UV-C treatment preserves quality with minimal effects on phenolic compounds and antioxidant capacity.[202] Conversely, changes in phenolic compounds have been reported in products such as grape juice; it has been emphasized that the mechanism of action of UV-C radiation depends on many factors including the type of food, surface properties, irradiation time, and composition.[284] Reports also indicate that UV-C can lead to structural softening in certain products, surface darkening, and losses in volatile compounds.[206,284]

Ozone ($O_3$) applications are one of the non-thermal technologies that stand out due to their potential to ensure microbial safety in foods, extend shelf life, and contribute to the preservation of certain bioactive components. In a study on juniper berries, it was noted that a 30 minute ozone application at a dose of 100 g $O_3$ per $m^3$ approximately doubled the total phenolic content; however, longer applications led to the degradation of phenolic compounds.[17] In the case of green cabbage, the combined use of ozone and ultrasound effectively inactivated pathogens such as *Escherichia coli* and *Salmonella* while preserving sensory and nutritional quality by maintaining vitamin C content and product color.[285] In cereal products, ozonation provides functional benefits including the removal of mycotoxins and the improvement of the rheological properties of the dough. However, the effects on ascorbic acid and phenolic compounds can differ depending on the application parameters.[286] In the storage and washing of vegetables, ozone applied in liquid and gas phases decreases surface contamination and extends shelf life; at the same time, it can largely preserve the natural appearance and sensory properties of the products.[287] However, high concentrations or prolonged applications can cause color, taste, and texture losses in some foods; this indicates that ozone needs to be optimized on a product basis.[211]

## 5. Effects on food safety and microbial risk management

The presence of many foodborne pathogenic diseases makes food safety a critical public health issue at the global level.[288] Non-thermal sterilization processes do not require the addition of chemicals that can cause residues in food and better preserve food quality.[289] Non-thermal processes have been shown to inactivate toxin-producing microorganisms through various mechanisms such as releasing reactive species, disrupting cell membrane integrity, affecting genetic materials, and degradation of molecular structures responsible for toxic effects.[290] Fig. 2 shows several effects of non-thermal treatments on pathogenic microorganisms.

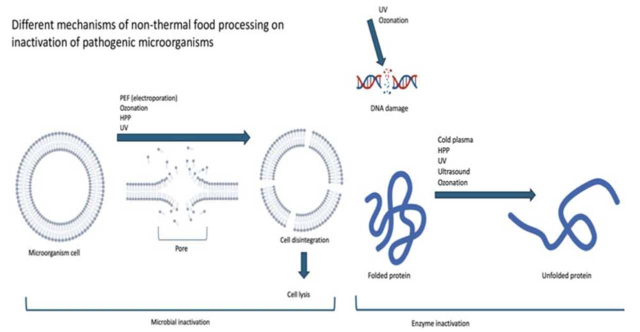


Fig. 2 Different mechanism of non-thermal food processing on inactivation of pathogenic microorganisms.

HHP processing is recognized as an effective method of microbial inactivation and the European Food Safety Authority (EFSA) has reported with 99–100% confidence that HHP does not pose an additional microbial safety risk to the consumer compared to routine food processing practices.[291] However, it has been reported that thermal pasteurization of milk did not achieve the expected reduction of more than 10 log10 in most pathogens such as *Mycobacterium bovis*, *Brucella melitensis*, *L. monocytogenes*, *Salmonella* spp. and Shiga toxin-producing *E. Coli* (STEC), *Campylobacter* spp, TBEV and *S. aureus* with HPP, but lower log10 reductions that meet the recommendations of international organizations.[292] For example, inactivation rates of *Escherichia coli*, *Salmonella* spp., *Staphylococcus aureus* and *Listeria monocytogenes* were 94.8%, 100.0%, 86.7% and 100.0%, respectively, in HHP-treated meat.[293] Moreover, in some foods with low water activity, like cured ham, the efficacy of HHP on *L. monocytogenes* may be limited. However, even in this case, no pathogen growth was observed during storage and the expression of relevant virulence genes was reported to decrease.[294] Dao *et al.*[228] showed that HPP treatment at 612 MPa, 11 minutes and 36 °C inactivated *E. coli* and *Listeria innocua* in pigmented rice grass juice. It was also shown that HPP treatment at 500 MPa for 9 minutes in human milk resulted in >5 log reduction in vegetative neonatal pathogens while retaining bioactive proteins including IgA, IgM, lactoferrin, elastase, PIGR and BSSL well.[295]

PEF is used for microbial inactivation of nutrients by electroporation. It has been shown to cause bacterial death by altering the permeability and fatty acid composition of the cell membrane, causing cells to change shape and shrink, leading to leakage of intracellular proteins, and affecting ROS and ATP synthesis.[296] It has revealed that it can be applied to inactivate *Staphylococcus aureus* and *Escherichia coli* in Thai orange juice.[297] Araújo *et al.* reported a similar reduction in viable *L. monocytogenes* cell count and a more significant reduction in *E. Coli* count in goat milk when comparing 64 °C pasteurization with PEF pretreatment to typical 72 °C pasteurization.[298] It has been stated that PEF technology may be effective in reducing the amount of sulfate used in winemaking owing to its effect in preventing microbial contamination after alcoholic and malolactic fermentation in red wine.[299] Cai *et al.*[296] showed that HVPEF treatment with high-voltage pulsed electrical fields combined with antibacterial agents can provide bacterial inactivation while reducing the dosage of antibacterial agents. Contradicting these studies, a study with edible insects showed that continuous PEF treatment with an energy of about 20 kJ $L^{-1}$ did not significantly reduce the microbial load in practical terms, while batch PEF treatment at higher energies (>150 kJ $kg^{-1}$) led to reductions in microbial load up to 5 logs, while causing heating up to 75 °C and affecting protein structure.[300]

The effect of ultrasound technology on the inactivation of pathogenic microorganisms has been confirmed and its combination with other non-thermal technologies (*e.g.* UV, PEF, ozone, microwave) has been reported to provide synergistic benefits.[301] In minimally processed winter jujube, the effect of ultrasound alone was limited, but the combination of ultrasound applied at a frequency of 28 kHz with free chlorine resulted in a significant reduction in microbial load during storage.[302] Sequential pulsed light (0.80 J $cm^{-2}$) and ultrasound (0.4 W $cm^{-3}$) reduced the *S. cerevisiae* population in sweet lemon juice by 6.2 log cycles and reduced polyphenol oxidase (PPO) activity by 90%, with 95% retention of vitamin C.[223] The combined effect of US and plasma activated water treatment (UP treatment) has been shown to inactivate microorganisms such as *Escherichia coli* O157:H7 and *Listeria monocytogenes* up to 3 log CFU $g^{-1}$ in fresh chopped celery by damaging the cell membrane.[303] Rodríguez *et al.*[304] reported that the combination of US (1440 s) and HPP (400 MPa for 2 min) showed a synergistic effect in orange juice, resulting in a 5 log CFU $mL^{-1}$ reduction in *Escherichia coli*. However, since the application parameters (such as frequency, temperature, sample volume, device type) can significantly influence the results, a standardized protocol for ultrasound is not yet available and has not been officially approved by regulatory bodies.[301,305]

Cold plasma treatments are also reported to provide high microbial inactivation, cause minimal changes in nutritional components as they are carried out at room temperature and leave no toxic residues.[293] Direct or indirect plasma applied to ricotta cheese extended the shelf life of the product up to two days.[306] Cold atmospheric plasma torch (CAPT) treatment of ready-to-eat Olivier salad significantly reduced the microbial load.[307] The combination of clove oil and encapsulated atmospheric pressure plasma was shown to have a strong antibacterial effect on *Escherichia coli* O157:H7 and *Staphylococcus aureus*.[308] Atmospheric oxygen and air cold plasma treatment has also been shown to successfully inactivate *Bacillus cereus* in foods with low water activity (soy powder, rice, black pepper).[309–311] Kim *et al.* conducted in-pack microbial inactivation of cabbage slices using a combination of hydrogen peroxide ($H_2O_2$) and atmospheric dielectric barrier discharge cold plasma (ADCP). This method resulted in 1.8 and 2.0 log CFU $g^{-1}$ reduction in *E. coli* O157:H7 and *Listeria monocytogenes*, respectively, and 1.0 and 1.3 log reduction in *Bacillus cereus* spores and local bacteria, respectively.[312]

UV-C prevents the formation of new DNA chains by causing photo-chemical damage to DNA, thus showing an antimicrobial effect.[313] UV-C LEDs are widely used to eliminate pathogenic microorganisms such as *Listeria monocytogenes*, *Staphylococcus aureus*, *Bacillus cereus*, *Escherichia coli* and *Salmonella Typhimurium* in water.[314,315] However, it has been shown to be ineffective in inactivating internal enzymes owing to its relatively poor penetration capacity.[316] UV-C-assisted washing effectively reduced *E. coli* and *Salmonella* pathogens, especially in products with smoother surfaces such as tomatoes, whereas the same effect was not observed in fresh-cut lettuce with rougher surface.[109] UV LED treatment of meat for 24 hours resulted in significant reductions in *E. coli*, *Salmonella* and *S. aureus* loads; however, no similar effect was obtained for *L. monocytogenes*.[293] UV-C treatment was shown to effectively inactivate *Alicyclobacillus* spp. spores and other microbial strains in textured orange juice;[317] and *E. coli* and *L. monocytogenes* in sweet lemon juice.[318] Borges *et al.*[319] reported that UV treatment of cured smoked meats reduced the number of *L. monocytogenes*, but had no effect on endogenous microbial populations. UV-C irradiation combined with peracetic acid (PAA) or lactic acid (LA) was found to significantly reduce *Salmonella enteritidis* biofilms on food contact surfaces and chicken skin.[320] However, Zhang *et al.* investigated the long-term persistence of three human rotavirus (HRV) strains on beef, chicken and lettuce and found that while UV-C irradiation was generally effective, its effect was inconsistent between different food surfaces. UV-C dose of 100 mJ $cm^{-2}$ resulted in >4 log10 reduction on lettuce but >1 log10 reduction on beef and chicken.[321] In one study examining the microbial inactivation of UV processing in tropical fruit juices, it was demonstrated that UV treatment resulted in >5 log reduction of *E. coli* in pineapple, starfruit, graviola, mango, passion fruit, naranjilla and carob beverages. However, UV did not significantly affect microbial spoilage indicators and carotenoid content in mango beverage compared to thermal pasteurization.[322]

Ozone technology provides effective microbial elimination by causing oxidative degradation of vital components of microorganisms.[313] It has been demonstrated that it can have a significant selectivity effect on bacteria in water and can reshape the bacterial community in reclaimed water.[323] For example, gaseous ozone applied to vacuum-packed beef kept the *L. monocytogenes* load below the detection limit for 16 days.[112] Souza Grilo *et al.*[324] showed that ozone reduced the titer of norovirus surrogate bacteriophage MS2 to 3.6 log PFU $g^{-1}$ in blackberry and 4.1 log PFU $g^{-1}$ in pitangada fruit. In the study of Zai *et al.*, treatment with 2% $H_2O_2$, 19 mJ $cm^{-2}$ UV-C dose and 20 ppm ozone as an alternative to conventional formaldehyde disinfection in incubation and table eggs was shown to inactivate Salmonella at a rate of 5 log CFU per egg.[325]

## 6. Can non-thermal processing optimize nutritional value, quality, and safety simultaneously?

The main advantage of non-thermal food processing technologies is that they do not only improve one attribute of food quality but can enhance multiple aspects simultaneously.[17] Non-thermal processing technologies, when properly designed and optimized, can largely eliminate traditionally existing trade-offs between nutritional value, microbial safety, and product quality. Sensory attributes including product texture, color, and aroma can be kept largely constant, along with the preservation of heat-sensitive vitamins, minerals, and bioactive compounds. At the same time, these technologies also contribute significantly to the reduction of chemical contaminants like pesticides, mycotoxins, and allergens.[326] However, in order to achieve these three main objectives simultaneously, the process parameters need to be carefully optimized specific to the product type and matrix, and often these technologies need to be used in combination with each other. Hence, non-thermal processing is not just a technical innovation but represents a comprehensive approach to food production that combines nutritional quality, safety, as well as environmental sustainability.[327,328]

Compared to heat treatment, HHP treatments achieve high success in microbial inactivation while preserving nutrients to a large extent; especially in liquid and semi-solid products, they can achieve this triple balance by preserving product texture and sensory quality.[31] PEF reduces microbial contamination by increasing cell permeability and increases the bioavailability of bioactive compounds such as phenolic compounds; however, it requires product-based optimization as its effect may be limited in solid foods.[329] Ultrasound works at low temperature, protecting heat-sensitive components while increasing antioxidant capacity and supporting quality by reducing processing time; however, the resulting temperature increase can affect sensory properties if not carefully controlled.[74] Cold plasma, works at low temperatures, ensuring microbial safety on the product surface and increasing the stability of compounds such as phenolics and vitamin C. However, the process conditions should be carefully determined as there is a risk of quality loss owing to oxidative stress in some products.[330] UV-C irradiation improves microbial safety, especially in surface and liquid foods, and when applied at low doses, it can support antioxidant capacity and maintain quality and nutritional value together; nonetheless, the dose and duration should be carefully optimized as light-sensitive vitamins may be lost.[77] Ozonation, conversely, can reduce both microbial and chemical contaminants due to its strong oxidative nature, and also contributes to functional quality by increasing phenolic stability; however, flavor and color changes can be observed in excessive applications.[3] In this context, although each method has its advantages and limitations, under appropriate conditions and when optimized according to the product type, non-thermal technologies are versatile systems that can simultaneously support nutritional value, quality and safety.[77]

In contrast, the comprehensive approach suggests that non-thermal technologies should be considered as integrated solutions rather than singular solutions.[77] For example, when targeting microbial inactivation, processes that simultaneously minimize vitamin loss and reduce pesticide residues should be preferred. Here, combined treatments such as PEF + CP, US + ozone, or UV-C + ozone can offer simultaneous improvements at different levels of food systems (nutrient protection, quality sustainability, toxic compound removal).[331–334] Moreover, a comprehensive approach requires a mindset that is not only product-centered but effective throughout the entire supply chain. Energy efficiency, reduction of water consumption, elimination of chemical additives, and reduction of food waste show that these technologies contribute to sustainability goals at a system scale.[333] Therefore, non-thermal technologies are becoming a strategic tool not only for shelf-life and quality optimization but also for the development of climate-friendly, low-carbon-footprint, healthy, and clean-label products.[330]

Non-thermal food processing approaches are effective in all processes from micro to macro: preservation of bioactive compounds at the molecular level, functional quality at the product level, efficiency at the process level, and sustainability at the system level. Consequently, for the future of food science and technology, a comprehensive approach is not just a choice but a strategic breakthrough in food technology.[335]

## 7 Conclusions

This article shows that non-thermal food processing methods like ozonation, pulsed electric field (PEF), high hydrostatic pressure (HHP), ultrasonication (US), cold plasma (CP), and UV-C irradiation have a lot of potential to make food healthier, more nutritious, and less likely to contain microorganisms. Compared to conventional thermal methods, these technologies enable better preservation of heat-sensitive vitamins, minerals, and bioactive compounds, while also contributing to shelf life extension and minimizing degradation of sensory and physicochemical properties. In addition, technologies such as CP, ozone, and UV-C have been reported to reduce chemical contaminants including pesticide residues, mycotoxins, and allergens. Each non-thermal method offers specific advantages in preserving macro- and micronutrients, enhancing bioavailability, improving functional quality, and ensuring microbial control. However, the effectiveness of these technologies varies depending on product type, matrix structure, and processing parameters. Hence, product-specific optimization strategies are essential to maximize their benefits. From a comprehensive perspective, combinations of non-thermal methods (*e.g.*, HHP + PEF, US + ozone, UV-C + CP) can provide simultaneous benefits such as nutrient protection, contaminant reduction, and environmental sustainability. These applications support circular economy principles and climate-friendly food systems through clean-label production, reduced energy use, and minimal chemical inputs.

Non-thermal technologies should not only be considered for improving process efficiency but also for the production of functional, enriched, and allergen-free foods; therefore, optimization studies tailored to specific food matrices should be expanded, and the synergistic effects of combined treatments should be further explored along with their industrial scalability. Moreover, the establishment of regulatory frameworks and the promotion of awareness efforts are essential to enhance consumer confidence.

## Conflicts of interest

There are no conflicts to declare.

 

## Data availability

No data available to share for this article since it is a review paper.

## Acknowledgements

The authors received no specific funding for this work.

## Notes and references

1 D. Knorr and H. Watzke, *Front. Nutr.*, 2019, **6**, 85.
2 P. Huebbe and G. Rimbach, *Foods*, 2020, **9**(8), 1056.
3 R. Iqbal and M. Thakur, in *Sustainable Food Systems (Volume II): SFS: Novel Sustainable Green Technologies, Circular Strategies, Food Safety & Diversity*, ed. M. Thakur, Springer Nature Switzerland, Cham, 2024, pp. 379–414, DOI: 10.1007/978-3-031-46046-3_19.
4 G. Ciptaan, I. M. Mirnawati, K. Fajrona and A. Srifani, *Int. J. Vet. Sci.*, 2024, **13**, 154–159.
5 Z. B. Al-Rawashdeh, J. A. Al-Dalaeen, M. B. AL-Nawaiseh, M. R. Karaje and S. A. Al-Dalain, *Int. J. Agric. Biosci.*, 2024, **13**, 540–546.
6 R. N. Arshad, Z. Abdul-Malek, U. Roobab, M. A. Munir, A. Naderipour, M. I. Qureshi, A. El-Din Bekhit, Z.-W. Liu and R. M. Aadil, *Trends Food Sci. Technol.*, 2021, **111**, 43–54.
7 N. N. Misra, M. Koubaa, S. Roohinejad, P. Juliano, H. Alpas, R. S. Inácio, J. A. Saraiva and F. J. Barba, *Food Res. Int.*, 2017, **97**, 318–339.
8 E. Sukmawinata, R. Laila, H. Pisestyani, S. Noor, E. Martindah, R. Widiastuti, S. Wahyuwardani, E. Kusumaningtyas, Andriani, M. Subangkit, D. Endrawati, T. Ariyanti and F. Rachmawati, *Int. J. Vet. Sci.*, 2025, **14**, 1–7.
9 B. Barbol, *Pak. Vet. J.*, 2025, **4**, 978–987.
10 R. I. Barbhuiya, P. Singha and S. K. Singh, *Food Res. Int.*, 2021, **149**, 110647.
11 Z.-H. Zhang, L.-H. Wang, X.-A. Zeng, Z. Han and C. S. Brennan, *Int. J. Food Sci. Technol.*, 2019, **54**, 1–13.
12 G. Abera, *Cogent Food Agric.*, 2019, **5**(1), 1568725.
13 P. Kulawik, R. N. Bhojraj, O. Yesim, O. Fatih and W. Zhang, *Crit. Rev. Food Sci. Nutr.*, 2023, **63**, 9716–9730.
14 B. Speranza, A. Racioppo, A. Bevilacqua, V. Buzzo, P. Marigliano, E. Mocerino, R. Scognamiglio, M. R. Corbo, G. Scognamiglio and M. Sinigaglia, *Foods*, 2021, **10**, 2854.
15 S. Harikrishna, P. P. Anil, R. Shams and K. K. Dash, *J. Agric. Food Res.*, 2023, **14**, 100747.
16 R. D. Tchonkouang, A. R. Lima, A. C. Quintino, N. L. Cristofoli and M. C. Vieira, *Foods*, 2023, **12**, 3227.
17 R. Pandiselvam, S. Mitharwal, P. Rani, M. A. Shanker, A. Kumar, R. Aslam, Y. T. Barut, A. Kothakota, S. Rustagi, D. Bhati, S. A. Siddiqui, M. W. Siddiqui, S. Ramniwas, A. Aliyeva and A. Mousavi Khaneghah, *Curr. Res. Food Sci.*, 2023, **6**, 100529.
18 M. L. Bhavya and H. U. Hebbar, in *Engineering Aspects of Food Quality and Safety*, ed. H. U. Hebbar, R. Sharma, R. S. Chaurasiya, S. Ranjan and K. S. M. S. Raghavarao, Springer International Publishing, Cham, 2023, pp. 115–161, DOI: 10.1007/978-3-031-30683-9_6.
19 B. Naveena and M. Nagaraju, *Int. J. Chem. Stud.*, 2020, **8**, 2964–2967.
20 C. A. Pinto, S. A. Moreira, L. G. Fidalgo, R. S. Inácio, F. J. Barba and J. A. Saraiva, *Compr. Rev. Food Sci. Food Saf.*, 2020, **19**, 553–573.
21 R. Sehrawat, B. P. Kaur, P. K. Nema, S. Tewari and L. Kumar, *Food Sci. Biotechnol.*, 2021, **30**, 19–35.
22 M. D'Arrigo, J. Delgado-Adámez, J. J. García-Parra, I. Palacios, M. López-Parra, A. I. Andrés and M. R. Ramírez-Bernabé, *Foods*, 2025, **14**, 594.
23 K. H. Bak, T. Bolumar, A. H. Karlsson, G. Lindahl and V. Orlien, *Crit. Rev. Food Sci. Nutr.*, 2019, **59**, 228–252.
24 E. Panel, o. B. Hazards, K. Koutsoumanis, A. Alvarez-Ordóñez, D. Bolton, S. Bover-Cid, M. Chemaly, R. Davies, A. De Cesare, L. Herman, F. Hilbert, R. Lindqvist, M. Nauta, L. Peixe, G. Ru, M. Simmons, P. Skandamis, E. Suffredini, L. Castle, M. Crotta, K. Grob, M. R. Milana, A. Petersen, A. X. Roig Sagués, F. Vinagre Silva, E. Barthélémy, A. Christodoulidou, W. Messens and A. Allende, *EFSA J.*, 2022, **20**, e07128.
25 U. Roobab, M. A. Shabbir, A. W. Khan, R. N. Arshad, A. E.-D. Bekhit, X.-A. Zeng, M. Inam-Ur-Raheem and R. M. Aadil, *LWT*, 2021, **149**, 111828.
26 V. A. Athira, E. Gokulvel, A. M. Nandhu Lal, V. V. Venugopalan, Rajkumar and T. Venkatesh, *Crit. Rev. Food Sci. Nutr.*, 2023, **63**, 10849–10865.
27 J. Ma, Y. Wang, M. Zhao, P. Tong, L. Lv, Z. Gao, J. Liu and F. Long, *Foods*, 2023, **12**, 441.
28 P. Pérez, S. Hashemi, M. Cano-Lamadrid, L. Martínez-Zamora, P. A. Gómez and F. Artés-Hernández, *Foods*, 2023, **12**, 3808.
29 U. Roobab, J. S. Chacha, A. Abida, S. Rashid, G. Muhammad Madni, J. M. Lorenzo, X.-A. Zeng and R. M. Aadil, *Foods*, 2022, **11**, 2173.
30 L. Giura, L. Urtasun, I. Astiasaran and D. Ansorena, *Foods*, 2023, **12**, 882.
31 U. Roobab, R. Afzal, M. M. A. N. Ranjha, X.-A. Zeng, Z. Ahmed and R. M. Aadil, *Int. J. Food Sci. Technol.*, 2021, **57**, 816–826.
32 N. Ozaybi, *Processes*, 2024, **12**, 2073.
33 C. Caner, R. Hernandez and B. Harte, *Packag. Technol. Sci.*, 2004, **17**, 23–29.
34 E. Grau-Fuentes, R. Garzón, D. Rodrigo and C. M. Rosell, *Food Res. Int.*, 2025, **201**, 115593.
35 B. G. Nabi, K. Mukhtar, R. N. Arshad, E. Radicetti, P. Tedeschi, M. U. Shahbaz, N. Walayat, A. Nawaz, M. Inam-Ur-Raheem and R. M. Aadil, *Sustainability*, 2021, **13**, 13908.
36 C. Zhang, X. Lyu, R. N. Arshad, R. M. Aadil, Y. Tong, W. Zhao and R. Yang, *Food Chem.*, 2023, **403**, 134367.
37 K. Mukhtar, B. G. Nabi, R. N. Arshad, U. Roobab, B. Yaseen, M. Ranjha, R. M. Aadil and S. A. Ibrahim, *Ultrason. Sonochem.*, 2022, **90**, 106194.
38 M. Rashvand, A. Kazemi, M. Nikzadfar, T. Javed, L. Luke, K. Kjær, A. Feyissa, C. Millman and H. Zhang, *Food Bioprocess Technol.*, 2025, **18**, 5117–5145.

39 Z. T. Al-Sharify, S. Z. Al-Najjar, C. K. Anumudu, A. Hart, T. Miri and H. Onyeaka, *Appl. Sci.*, 2025, **15**, 3049.
40 Z. Alkanan, A. Altemimi, M. Younis, M. Ali, F. Cacciola and T. Abedelmaksoud, *ChemBioEng Rev.*, 2024, **11**(4), e202300078.
41 G. López-Gámez, P. Elez-Martinez, O. Martin-Belloso and R. Soliva-Fortuny, *Food Chem.*, 2021, **364**, 130377.
42 A. Akyıldız, B. Dundar Kirit and E. Ağçam, in *Natural Products in Beverages: Botany, Phytochemistry, Pharmacology and Processing*, ed. J.-M. Mérillon, C. Riviere and G. Lefèvre, Springer International Publishing, Cham, 2023, pp. 1–29.
43 A. Taha, F. Casanova, P. Šimonis, V. Stankevič, M. A. E. Gomaa and A. Stirkė, *Foods*, 2022, **11**, 1556.
44 M. Trusinska, F. Drudi, K. Rybak, U. Tylewicz and M. Nowacka, *Foods*, 2023, **12**(21), 3957.
45 B. Llavata Cabrero, R. Mello, A. Quiles, J. Corrêa and J. Cárcel, *npj Sci. Food*, 2024, **8**, 56.
46 K. Pobiega, A. Matys, M. Trusinska, K. Rybak, D. Witrowa-Rajchert and M. Nowacka, *Appl. Sci.*, 2023, **13**, 12335.
47 B. Llavata, R. E. Mello, A. Quiles, J. L. G. Correa and J. A. Cárcel, *npj Sci. Food*, 2024, **8**, 56.
48 R. N. Arshad, Z. Abdul-Malek, A. Munir, Z. Buntat, M. H. Ahmad, Y. M. M. Jusoh, A. E.-D. Bekhit, U. Roobab, M. F. Manzoor and R. M. Aadil, *Trends Food Sci. Technol.*, 2020, **104**, 1–13.
49 S.-H. Jeong, H.-B. Lee and D.-U. Lee, *Food Sci. Anim. Resour.*, 2024, **44**(2), 239–254.
50 S. Kumar, J. Konwar, M. D. Purkayastha, S. Kalita, A. Mukherjee and J. Dutta, *Int. J. Biol. Macromol.*, 2023, **239**, 124332.
51 Y. Feng, T. Yang, Y. Zhang, A. Zhang, L. Gai and D. Niu, *Front. Nutr.*, 2022, **9**, 1048632.
52 F. Punthi, B. Yudhistira, M. Gavahian, C.-K. Chang, K.-C. Cheng, C.-Y. Hou and C.-W. Hsieh, *Compr. Rev. Food Sci. Food Saf.*, 2022, **21**, 5109–5130.
53 U. Roobab, A. Abida, J. S. Chacha, A. Athar, G. M. Madni, M. Ranjha, A. V. Rusu, X. A. Zeng, R. M. Aadil and M. Trif, *Molecules*, 2022, **27**(13), 35807277.
54 S. Kumar, J. Konwar, M. D. Purkayastha, S. Kalita, A. Mukherjee and J. Dutta, *Int. J. Biol. Macromol.*, 2023, **239**, 124332.
55 V. Athanasiadis, T. Chatzimitakos, K. Kotsou, D. Kalompatsios, E. Bozinou and S. I. Lalas, *Int. J. Mol. Sci.*, 2023, **24**, 15914.
56 A. Bebek Markovinović, V. Stulić, P. Putnik, A. Birkić, M. Jambrović, D. Šaško, J. Ljubičić, B. Pavlić, Z. Herceg and D. Bursać Kovačević, *Foods*, 2023, **12**, 3172.
57 G. V. Barbosa-Cánovas, J. M. Aguilera, X. D. Chen, R. W. Hartel, A. Ibarz, J. Kokini, M. Marcotte, M. McCarthy, K. Niranjan and M. Peleg, *Food Engineering Series*, Springer, 2020.
58 C. Zhou, C. E. Okonkwo, A. A. Inyinbor, A. E. A. Yagoub and A. F. Olaniran, *Crit. Rev. Food Sci. Nutr.*, 2023, **63**, 1587–1611.
59 N. Bhargava, R. S. Mor, K. Kumar and V. S. Sharanagat, *Ultrason. Sonochem.*, 2021, **70**, 105293.
60 T. J. Mason, *Ultrason. Sonochem.*, 2016, **29**, 519–523.
61 N. Y. A. Prempeh, X. Nunekpeku, A. Murugesan and H. Li, *Foods*, 2025, **14**, 2057.
62 M. M. A. N. Ranjha, S. Irfan, J. M. Lorenzo, B. Shafique, R. Kanwal, M. Pateiro, R. N. Arshad, L. Wang, G. A. Nayik, U. Roobab and R. M. Aadil, *Processes*, 2021, **9**, 1406.
63 C. Zhou, C. E. Okonkwo, A. A. Inyinbor, A. E. G. A. Yagoub and A. F. Olaniran, *Crit. Rev. Food Sci. Nutr.*, 2023, **63**, 1587–1611.
64 A. Kot and A. Kamińska-Dwórznicka, *Appl. Sci.*, 2024, **14**, 8689.
65 M. Sun, Y. Xu, Y. Ding, Y. Gu, Y. Zhuang and X. Fan, *Foods*, 2023, **12**, 2705.
66 R. Sasikumar, I. B. Mangang, K. Vivek and A. K. Jaiswal, *J. Food Process Eng.*, 2023, **46**, e14468.
67 G. C. Jeevitha, R. Saravanan, A. Mittal and S. V. Kumar, *Discover Food*, 2023, **3**, 26.
68 Y. A. d. A. Bernardo, D. K. A. do Rosario and C. A. Conte-Junior, *Foods*, 2023, **12**, 476.
69 F. Tahir, F. Fatima, R. Fatima and E. Ali, *Agrobiological Records*, 2023, **10**, 1–8.
70 K. Rueangsri, P. Lasunon, S. Kwantrairat and N. Taweejun, *Int. J. Agric. Biosci.*, 2025, **14**, 1–10.
71 A. R. Bariya, N. B. Rathod, A. S. Patel, J. K. B. Nayak, R. C. Ranveer, A. Hashem, E. F. Abd Allah, F. Ozogul, A. R. Jambrak and J. M. Rocha, *Ultrason. Sonochem.*, 2023, **101**, 106676.
72 J. Qian, D. Chen, Y. Zhang, X. Gao, L. Xu, G. Guan and F. Wang, *Foods*, 2023, **12**, 4027.
73 X. Zhang, D. Yan, W. Qiu, S. Chen, Y. Hu, J. Jin and C. C. Udenigwe, *Int. J. Biol. Macromol.*, 2024, **283**, 137874.
74 K. J. E.-P. Kouamé, E. O. Falade, Y. Zhu, Y. Zheng and X. Ye, *Food Chem.*, 2025, **476**, 143326.
75 N. Mahmood, B. Muhoza, A. Kothakot, Z. Munir, Y. Huang, Y. Zhang, R. Pandiselvam, S. Iqbal, S. Zhang and Y. Li, *Compr. Rev. Food Sci. Food Saf.*, 2024, **23**, e13286.
76 H. Yu, Q. Zhong, Y. Liu, Y. Guo, Y. Xie, W. Zhou and W. Yao, *Ultrason. Sonochem.*, 2020, **64**, 104844.
77 N. Nayak, R. R. Bhujle, N. A. Nanje-Gowda, S. Chakraborty, K. Siliveru, J. Subbiah and C. Brennan, *Heliyon*, 2024, **10**, e30921.
78 A. Taha, M. Taha, P. Ravi, A. S. Shahida, A. M. Nisar, M. M. Ahmad, O. J. Sujayasree, A. K. Chaitanya, K. A. Chandra, C. Federico, X. Xiaoyun, P. Siyi and H. Hu, *Crit. Rev. Food Sci. Nutr.*, 2024, **64**, 6016–6054.
79 N. U. Sruthi, K. Josna, R. Pandiselvam, A. Kothakota, M. Gavahian and A. Mousavi Khaneghah, *Food Chem.*, 2022, **368**, 130809.
80 E. Özdemir, P. Başaran, S. Kartal and T. Akan, *Compr. Rev. Food Sci. Food Saf.*, 2023, **22**, 4484–4515.
81 F. Fernandes and S. Rodrigues, *Sustainable Food Technol.*, 2024, **3**, 32–53.
82 R. Mandal, A. Singh and A. Pratap-Singh, *Trends Food Sci. Technol.*, 2018, **80**, 93–103.
83 N. Yawut, T. Mekwilai, N. Vichiansan, S. Braspaiboon, K. Leksakul and D. Boonyawan, *J. Agric. Food Res.*, 2024, **18**, 101383.

84 D. Laroque, S. Seó, G. Ayala Valencia, J. Laurindo and B. Carciofi, *J. Food Eng.*, 2022, **312**, 110748.
85 R. Sasikumar, S. K. T, I. B. Mangang, G. Kaviarasu, R. Kaushik, P. Mansingh, V. Tomer and A. K. Jaiswal, *Sustainable Food Technol.*, 2025, DOI: 10.1039/D5FB00148J.
86 B. Li, L. Peng, Y. Cao, S. Liu, Y. Zhu, J. Dou, Z. Yang and C. Zhou, *Foods*, 2024, **13**, 1522.
87 A. Ramu Ganesan, U. Tiwari, P. Ezhilarasi and G. Rajauria, *J. Food Process. Preserv.*, 2020, **45**, e15070.
88 A. Barjasteh, N. Kaushik, E. H. Choi and N. K. Kaushik, *Int. J. Mol. Sci.*, 2024, **25**, 6638.
89 N. Santos, R. Almeida, T. Lima, J. Figueira, A. Martins, L. Silva, C. Marques, A. Meira, A. Araújo, B. de Melo, M. Mota, T. Gusmão, S. Sousa, J. Gomes and A. Rocha, *Food Biosci.*, 2025, **68**, 106719.
90 H. Yuan, F. Chen, J. Zhang, X. Guo, J. Zhang and W. Yan, *Foods*, 2025, **14**, 550.
91 Y. Hu, Y. Zhu, H. Aalim, Y. Cao, L. Peng, J. Dou, Y. Ma, X. Zhai, Z. Guo, J. Cai, C. Zhou, S. Liu and X. Zou, *Food Biosci.*, 2024, **60**, 104492.
92 H. Liu, X. Zhang, Z. Cui, Y. Ding, L. Zhou and X. Zhao, *Food Res. Int.*, 2022, **159**, 111655.
93 R. Kaavya, G. Mohsen, J. Surangna, K. A. Chandra, S. Pratiksha, K. Anjineyulu, K. Manoj, K. A. Mousavi, N. G. Ahmad, D. A. Hussain, U. Jalal, A. M. Javed and H. A. Hemeg, *Crit. Rev. Food Sci. Nutr.*, 2023, **63**, 11370–11384.
94 J. d. A. Bezerra, C. V. Lamarão, E. A. Sanches, S. Rodrigues, F. A. N. Fernandes, G. L. P. A. Ramos, E. A. Esmerino, A. G. Cruz and P. H. Campelo, *Food Res. Int.*, 2023, **167**, 112663.
95 M. Zhang, J. K. Oh, L. Cisneros-Zevallos and M. Akbulut, *J. Food Eng.*, 2013, **119**, 425–432.
96 M. Umair, J. Saqib, A. Zubaria, M. A. Rana, A. Muhammad, Z. Jianhao and Z. Liqing, *Food Rev. Int.*, 2022, **38**, 789–811.
97 K. K. Gupta and W. Routray, *Food Chem.*, 2025, **472**, 142960.
98 X. Yepez, A. E. Illera, H. Baykara and K. Keener, *Foods*, 2022, **11**, 1833.
99 M. Nikzadfar, A. Kazemi, R. Abooei, R. Abbaszadeh, M. Soltani Firouz, A. Akbarnia and M. Rashvand, *Food Bioprocess Technol.*, 2024, **17**, 4473–4505.
100 M. E. Oner, B. Gultekin Subasi, G. Ozkan, T. Esatbeyoglu and E. Capanoglu, *Food Res. Int.*, 2023, **172**, 113079.
101 A. Shelar, A. V. Singh, P. Dietrich, R. S. Maharjan, A. Thissen, P. N. Didwal, M. Shinde, P. Laux, A. Luch, V. Mathe, T. Jahnke, M. Chaskar and R. Patil, *RSC Adv.*, 2022, **12**, 10467–10488.
102 T. Dai, M. S. Vrahas, C. K. Murray and M. R. Hamblin, *Expert Rev. Anti-Infect. Ther.*, 2012, **10**, 185–195.
103 F. Salazar, S. Pizarro-Oteíza, I. Kasahara, M. Labbé, C. Estay, M. E. Tarnok, L. Aguilar and R. A. Ibáñez, *J. Food Process Eng.*, 2024, **47**, e14629.
104 Y. Lee and Y. Yoon, *Food Sci. Anim. Resour.*, 2024, **44**, 19–38.
105 B. Bisht, P. Bhatnagar, P. Gururani, V. Kumar, M. S. Tomar, R. Sinhmar, N. Rathi and S. Kumar, *Trends Food Sci. Technol.*, 2021, **114**, 372–385.
106 Y. Wang, A. Zhou, B. Yu and X. Sun, *Foods*, 2024, **13**, 2244.
107 H. B. Jadhav, U. S. Annapure and R. R. Deshmukh, *Front. Nutr.*, 2021, **8**, 2021.
108 T. K. Ranjitha Gracy, P. S. Sharanyakanth and M. Radhakrishnan, *Crit. Rev. Food Sci. Nutr.*, 2022, **62**, 1782–1799.
109 J. Wang and Z. Wu, *LWT*, 2023, **182**, 114901.
110 P. Suthiluk, N. Chuensombat, S. Setha and M. Naradisorn, *Front. Sustain. Food Syst.*, 2023, **7**, 2023.
111 V. Yemmireddy, A. Adhikari and J. Moreira, *Front. Nutr.*, 2022, **9**, 871243.
112 B. Giménez, N. Graiver, L. Giannuzzi and N. Zaritzky, *Food Control*, 2021, **121**, 107602.
113 H. Hong, M. F. Rizzi, D. Wang, L. McLandsborough and J. Lu, *Foods*, 2024, **13**, 3906.
114 P. Dubey, A. Singh and O. Yousuf, *Food Bioprocess Technol.*, 2022, **15**, 2102–2113.
115 Z. Hamid, B. K. Meyrick, J. Macleod, E. A. Heath and J. Blaxland, *Lett. Appl. Microbiol.*, 2024, **77**(11), ovae101.
116 E. I. Epelle, A. Macfarlane, M. Cusack, A. Burns, J. A. Okolie, W. Mackay, M. Rateb and M. Yaseen, *Chem. Eng. J.*, 2023, **454**, 140188.
117 R. Pandiselvam, R. Kaavya, Y. Jayanath, K. Veenuttranon, P. Lueprasitsakul, V. Divya, A. Kothakota and S. V. Ramesh, *Trends Food Sci. Technol.*, 2020, **97**, 38–54.
118 T. El-Desouky, *Discover Food*, 2025, **5**(1), 194.
119 U. Roobab, J. S. Chacha, A. Abida, S. Rashid, G. Muhammad Madni, J. M. Lorenzo, X. A. Zeng and R. M. Aadil, *Foods*, 2022, **11**(15), 2173.
120 N. Tanwar, B. K. Bhavana, S. N. Mudliar, P. Bhatt, P. Vasu and S. Debnath, *Food Control*, 2025, **177**, 111408.
121 P. Pal and A. Kioka, *Compr. Rev. Food Sci. Food Saf.*, 2025, **24**, e70133.
122 J. Wang, S. Yuan, X. Dai and B. Dong, *Chemosphere*, 2023, **319**, 138018.
123 M. G. Anjaly, M. V. Prince, A. S. Warrier, A. M. N. Lal, N. K. Mahanti, R. Pandiselvam, R. Thirumdas, R. Sreeja, A. V. Rusu, M. Trif and A. Kothakota, *Ultrason. Sonochem.*, 2022, **90**, 106166.
124 R. Bocker and E. K. Silva, *Food Chem.: X*, 2022, **15**, 100398.
125 B. Gómez, P. E. S. Munekata, M. Gavahian, F. J. Barba, F. J. Martí-Quijal, T. Bolumar, P. C. B. Campagnol, I. Tomasevic and J. M. Lorenzo, *Food Res. Int.*, 2019, **123**, 95–105.
126 A. C. Khanashyam, M. A. Shanker, A. Kothakota, N. K. Mahanti and R. Pandiselvam, *Ozone: Sci. Eng.*, 2021, **44**(1), 50–65.
127 R. I. Barbhuiya, P. Singha and S. K. Singh, *Food Res. Int.*, 2021, **149**, 110647.
128 H. Rostamabadi, A. C. Karaca, M. Nowacka, M. Z. Mulla, H. Al-Attar, K. Rathnakumar, B. G. Subasi, R. Sehrawat, A. Kheto and S. R. Falsafi, *Food Hydrocolloids*, 2023, **137**, 108375.
129 P. Kaur and U. S. Annapure, *Int. J. Biol. Macromol.*, 2024, **268**, 131615.
130 I. Sifuentes-Nieves, G. Mendez-Montealvo, P. C. Flores-Silva, M. Nieto-Pérez, G. Neira-Velazquez, O. Rodriguez-

Fernandez, E. Hernández-Hernández and G. Velazquez, *Innovative Food Sci. Emerging Technol.*, 2021, **68**, 102630.
131 R. Bajaj, N. Singh, A. Ghumman, A. Kaur and H. N. Mishra, *Starch/Staerke*, 2022, **74**, 2100096.
132 J. Zhang, M. Zhang, C. Wang, Y. Zhang, X. Bai, Y. Zhang and J. Zhang, *Int. J. Food Sci. Technol.*, 2022, **57**, 1888–1901.
133 X. Zhou, J. Chen, S. Wang and Y. Zhou, *Food Chem.*, 2022, **382**, 132324.
134 J. W. Park, J. H. Seo, C. Y. Hong, M. Y. Kim, Y. J. Lee, A.-R. Chun, Y. R. Lee, J. Lee and H. S. Jeong, *J. Food Qual.*, 2021, **2021**, 8838131.
135 F. Zhu and H. Li, *LWT*, 2019, **114**, 108367.
136 J. Liu, J. Bi, D. J. McClements, X. Liu, J. Yi, J. Lyu, M. Zhou, R. Verkerk, M. Dekker and X. Wu, *Carbohydr. Polym.*, 2020, **250**, 116890.
137 G. J. Fadimu, T. T. Le, H. Gill, A. Farahnaky, O. O. Olatunde and T. Truong, *Foods*, 2022, **11**, 1823.
138 N. T. Demirok and S. Yıkmış, *Processes*, 2022, **10**, 2100.
139 S. G. Anema, *Food Chem. Adv.*, 2022, **1**, 100002.
140 Y. Liu, M. Huang, X. Liu and M. Hu, *Innovative Food Sci. Emerging Technol.*, 2023, **84**, 103262.
141 K.-C. Hsieh and Y. Ting, *Food Chem.*, 2024, **441**, 138115.
142 Q. Chen, L. Dong, Y. Li, Y. Liu, Q. Xia, S. Sang, Z. Wu, J. Xiao, L. Liu and L. Liu, *Crit. Rev. Food Sci. Nutr.*, 2024, **64**, 7045–7066.
143 H. Rostamabadi, M. Nowacka, R. Colussi, S. F. Frasson, I. Demirkesen, B. Mert, P. Singha, S. K. Singh and S. R. Falsafi, *Trends Food Sci. Technol.*, 2023, **141**, 104208.
144 J. M. Pérez-Andrés, M. de Alba, S. M. Harrison, N. P. Brunton, P. Cullen and B. K. Tiwari, *Lwt*, 2020, **118**, 108697.
145 X. Wang, Z. Wang, H. Zhuang, M. M. Nasiru, Y. Yuan, J. Zhang and W. Yan, *Meat Sci.*, 2021, **176**, 108456.
146 Q. Zheng, H. Wang, L. Yue, W. Yan, H. Guo, Z. Chen, W. Qi and Q. Kong, *Radiat. Phys. Chem.*, 2022, **191**, 109851.
147 M. Uyarcan and S. C. Güngör, *Int. J. Biol. Macromol.*, 2024, **282**, 137085.
148 B. C. Maniglia, N. Castanha, P. Le-Bail, A. Le-Bail and P. E. D. Augusto, *Crit. Rev. Food Sci. Nutr.*, 2021, **61**, 2482–2505.
149 Q. Xia, B. D. Green, Z. Zhu, Y. Li, S. M. T. Gharibzahedi, S. Roohinejad and F. J. Barba, *Crit. Rev. Food Sci. Nutr.*, 2019, **59**, 3349–3370.
150 S. Öğüt, M. Türkol, S. Yıkmış, E. Bozgeyik, G. Abdi, E. Kocyigit, R. M. Aadil, N. Seyidoglu, D. Karakçı and N. Tokatlı, *Ultrason. Sonochem.*, 2025, **114**, 107245.
151 K. Ho and B. W. Redan, *Crit. Rev. Food Sci. Nutr.*, 2022, **62**, 508–526.
152 S. O. Serna-Hernandez, Z. Escobedo-Avellaneda, R. García-García, M. J. Rostro-Alanis and J. Welti-Chanes, *Foods*, 2022, **27**, 7179.
153 Y. Wang, C.-m. Ma, Y. Yang, B. Wang, X.-f. Liu, Y. Wang, X. Bian, G. Zhang and N. Zhang, *Food Res. Int.*, 2024, **195**, 114991.
154 M. A. Pitino, S. Unger, A. Doyen, Y. Pouliot, S. Aufreiter, D. Stone, A. Kiss and D. L. O'Connor, *J. Nutr.*, 2019, **149**, 497–504.
155 M. Y. Kim, S. H. Lee, G. Y. Jang, M. Li, Y. R. Lee, J. Lee and H. S. Jeong, *Food Chem.*, 2017, **217**, 106–111.
156 N. Naderi, A. Doyen, J. D. House and Y. Pouliot, *Food Chem.*, 2017, **232**, 253–262.
157 Q. Xia and Y. Li, *Food Res. Int.*, 2018, **106**, 817–824.
158 T. Yu, X. Zhang, R. Feng, C. Wang, X. Wang and Y. Wang, *Foods*, 2022, **11**, 2837.
159 Q. Xia, L. Wang, C. Xu, J. Mei and Y. Li, *Food Chem.*, 2017, **214**, 533–542.
160 C. Y. Wang, Y. T. Wang, S. J. Wu and Y. T. Shyu, *J. Food Sci. Technol.*, 2018, **55**, 5115–5122.
161 G. López-Gámez, P. Elez-Martínez, O. Martín-Belloso and R. Soliva-Fortuny, *Foods*, 2021, **10**(6), 1321.
162 H.-W. Huang, C.-P. Hsu and C.-Y. Wang, *J. Food Drug Anal.*, 2020, **28**, 1–13.
163 K. Aganovic, C. Hertel, R. F. Vogel, R. Johne, O. Schlüter, U. Schwarzenbolz, H. Jäger, T. Holzhauser, J. Bergmair, A. Roth, R. Sevenich, N. Bandick, S. E. Kulling, D. Knorr, K.-H. Engel and V. Heinz, *Compr. Rev. Food Sci. Food Saf.*, 2021, **20**, 3225–3266.
164 A. Ciurzynska, M. Trusinska, K. Rybak, A. Wiktor and M. Nowacka, *Molecules*, 2023, **28**, 2970.
165 L. Wang, Z. Li, D. Liu and J. Fan, *J. Sci. Food Agric.*, 2023, **103**, 1514–1521.
166 G. Ozkan, A. S. Stübler, K. Aganovic, G. Dräger, T. Esatbeyoglu and E. Capanoglu, *Food Chem.*, 2021, **360**, 129918.
167 D. Niu, X. A. Zeng, E. F. Ren, F. Y. Xu, J. Li, M. S. Wang and R. Wang, *Food Res. Int.*, 2020, **137**, 109715.
168 I. P. C. Brito and E. K. Silva, *Food Res. Int.*, 2024, **184**, 114207.
169 G. P. Shinde, R. Kumar, K. R. Reddy, S. Nadanasabhapathi and A. Dutt Semwal, *J. Food Sci. Technol.*, 2022, **59**, 1931–1938.
170 U. Pankiewicz, M. Sujka, R. Kowalski, A. Mazurek, M. Włodarczyk-Stasiak and J. Jamroz, *Food Chem.*, 2017, **221**, 1361–1370.
171 G. Nasir, S. Zaidi, S. Ahmad, F. M. Allai, F. Ahmad and A. Tarafdar, *Crit. Rev. Food Sci. Nutr.*, 2024, 1–18, DOI: 10.1080/10408398.2024.2405992.
172 F. Chen, M. Zhang and C. H. Yang, *Ultrason. Sonochem.*, 2020, **63**, 104953.
173 L. Cassani, B. Tomadoni and M. Del Rosario Moreira, *J. Sci. Food Agric.*, 2020, **100**, 5518–5526.
174 Y. Xu, D. Wang, W. Zhao, Y. Zheng, Y. Wang, P. Wang, Y. Ma and X. Zhao, *Food Chem.*, 2022, **380**, 132190.
175 X. Brenes, M. Guevara, E. Wong, C. Cortés, J. Usaga and C. Rojas-Garbanzo, *Food Sci. Technol. Int.*, 2022, **28**, 694–702.
176 A. Starek, Z. Kobus, A. Sagan, B. Chudzik, J. Pawłat, M. Kwiatkowski, P. Terebun and D. Andrejko, *Sci. Rep.*, 2021, **11**, 3488.
177 N. Bhargava, R. S. Mor, K. Kumar and V. S. Sharanagat, *Ultrason. Sonochem.*, 2021, **70**, 105293.
178 A. R. Al-Hilphy, A. B. Al-Temimi, H. H. M. Al Rubaiy, U. Anand, G. Delgado-Pando and N. Lakhssassi, *J. Food Sci.*, 2020, **85**, 1386–1396.

 

179 B. Xu, E. Sylvain Tiliwa, W. Yan, S. M. Roknul Azam, B. Wei, C. Zhou, H. Ma and B. Bhandari, *Food Res. Int.*, 2022, **152**, 110744.
180 M. Soltani Firouz, A. Farahmandi and S. Hosseinpour, *Ultrason. Sonochem.*, 2019, **57**, 73–88.
181 G. Bao, J. Niu, S. Li, L. Zhang and Y. Luo, *Ultrason. Sonochem.*, 2022, **82**, 105864.
182 D. Huang, K. Men, D. Li, T. Wen, Z. Gong, B. Sunden and Z. Wu, *Ultrason. Sonochem.*, 2020, **63**, 104950.
183 S. Kumar, S. Pipliya, P. P. Srivastav, B. Srivastava, S. R. Battula and R. Sen, *J. Food Sci.*, 2024, **89**, 6127–6141.
184 Y. Hou, R. Wang, Z. Gan, T. Shao, X. Zhang, M. He and A. Sun, *Food Chem.*, 2019, **290**, 79–86.
185 D. R. G. de Castro, J. M. Mar, L. S. da Silva, K. A. da Silva, E. A. Sanches, J. de Araújo Bezerra, S. Rodrigues, F. A. N. Fernandes and P. H. Campelo, *Food Res. Int.*, 2020, **131**, 109044.
186 K. F. L. A, T. V. Fonteles, B. A. R. M. T, G. Silvestre da Silva, E. Sousa de Brito, E. G. Alves Filho, F. A. N. Fernandes and S. Rodrigues, *Food Res. Int.*, 2021, **147**, 110479.
187 S. Jia, N. Zhang, H. Ji, X. Zhang, C. Dong, J. Yu, S. Yan, C. Chen and L. Liang, *Foods*, 2022, **11**(24), 4088.
188 Y. Ji, W. Hu, J. Liao, A. Jiang, Z. Xiu, S. Gaowa, Y. Guan, X. Yang, K. Feng and C. Liu, *J. Sci. Food Agric.*, 2020, **100**, 5586–5595.
189 E. Pogorzelska-Nowicka, E. Górska-Horczyczak, M. Hanula, M. Marcinkowska-Lesiak, G. Pogorzelski, A. Wierzbicka and A. Półtorak, *Meat Sci.*, 2022, **194**, 108988.
190 Y. Ding, W. Mo, Z. Deng, B. M. Kimatu, J. Gao and D. Fang, *Life*, 2022, **13**(1), 70.
191 D. D. Jayasena, T. Kang, K. N. Wijayasekara and C. Jo, *Food Sci. Anim. Resour.*, 2023, **43**, 1087–1110.
192 C. Sarangapani, D. Ryan Keogh, J. Dunne, P. Bourke and P. J. Cullen, *Food Chem.*, 2017, **235**, 324–333.
193 C. M. G. Charoux, A. Patange, S. Lamba, C. P. O'Donnell, B. K. Tiwari and A. G. M. Scannell, *J. Appl. Microbiol.*, 2021, **130**, 325–340.
194 S. Jaddu, S. Sonkar, D. Seth, M. Dwivedi, R. C. Pradhan, G. Goksen, P. Kumar Sarangi and A. Režek Jambrak, *Food Chem.: X*, 2024, **22**, 101266.
195 F. Hashempour-Baltork, A. Mirza Alizadeh, M. Taghizadeh and H. Hosseini, *Heliyon*, 2024, **10**, e40460.
196 Y. Chen, Y. Chen, Y. Fang, Z. Pei and W. Zhang, *Food Chem.*, 2024, **430**, 137045.
197 G. R. Warne, P. M. Williams, H. Q. Pho, N. N. Tran, V. Hessel and I. D. Fisk, *J. Food Sci.*, 2021, **86**, 3762–3777.
198 G. Hu, H. Liu, Y. Zhu, M. Hernandez, T. Koutchma and S. Shao, *Food Chem.*, 2018, **269**, 342–346.
199 R. R. Franco, G. A. Ojeda, K. M. Rompato and S. C. Sgroppo, *Food Sci. Technol. Int.*, 2023, **29**, 50–61.
200 M. Darré, A. R. Vicente, L. Cisneros-Zevallos and F. Artés-Hernández, *Foods*, 2022, **11**(5), 653.
201 R. D. Tchonkouang, A. R. Lima, A. C. Quintino, N. L. Cristofoli and M. C. Vieira, *Foods*, 2023, **12**(17), 3227.
202 J. Pierscianowski, V. Popović, M. Biancaniello, S. Bissonnette, Y. Zhu and T. Koutchma, *Food Res. Int.*, 2021, **140**, 110085.
203 W. Guan, J. Zhang, R. Yan, S. Shao, T. Zhou, J. Lei and Z. Wang, *Food Chem.*, 2016, **210**, 129–134.
204 N. Liang, H. Mohamed, R. F. Pung, J. Waite-Cusic and D. C. Dallas, *J. Agric. Food Chem.*, 2024, **72**, 12198–12208.
205 A. S. López-Díaz, O. Antonio-Gutiérrez, E. Palou, E. Mani-López, A. López-Malo and N. Ramírez-Corona, *Food Chem.*, 2025, **470**, 142678.
206 K. Pravallika, S. Pradhan, A. Prabha and S. Chakraborty, *Compr. Rev. Food Sci. Food Saf.*, 2025, **24**, e70107.
207 J. Shi, H. Cai, Z. Qin, X. Li, S. Yuan, X. Yue, Y. Sui, A. Sun, J. Cui, J. Zuo and Q. Wang, *Food Res. Int.*, 2023, **170**, 113020.
208 O. Basara and J. Gorzelany, *Molecules*, 2024, **29**(15), 3616.
209 V. Goffi, L. Zampella, R. Forniti, M. Petriccione and R. Botondi, *J. Sci. Food Agric.*, 2019, **99**, 5654–5661.
210 S. Swami, R. Muzammil, S. Saha, A. Shabeer, D. Oulkar, K. Banerjee and S. B. Singh, *Environ. Monit. Assess.*, 2016, **188**, 301.
211 A. J. Brodowska, A. Nowak and K. Śmigielski, *Crit. Rev. Food Sci. Nutr.*, 2018, **58**, 2176–2201.
212 S. Roshanak, M. Maleki, M. A. Sani, M. Tavassoli, Z. Pirkhezranian and F. Shahidi, *Int. J. Food Microbiol.*, 2023, **388**, 110066.
213 N. B. Rathod, R. C. Ranveer, P. K. Bhagwat, F. Ozogul, S. Benjakul, S. Pillai and U. S. Annapure, *Compr. Rev. Food Sci. Food Saf.*, 2021, **20**, 4407–4425.
214 G. Toydemir, B. G. Subasi, R. D. Hall, J. Beekwilder, D. Boyacioglu and E. Capanoglu, *Food Chem.: X*, 2022, **14**, 100334.
215 M. Nowacka, M. Dadan and U. Tylewicz, *Appl. Sci.*, 2021, **11**, 1269.
216 B. Erdal, R. B. Akalın, B. Yılmaz, E. Bozgeyik and S. Yıkmış, *J. Food Process. Preserv.*, 2022, **46**, e16952.
217 A. Núñez-Delgado, V. M. Mizrachi-Chávez, J. Welti-Chanes, S. T. Macher-Quintana and C. Chuck-Hernández, *Front. Nutr.*, 2023, **10**, 1325863.
218 G. E. Moro, M. Girard, C. Peila, N. Garcia, D. Escuder-Vieco, K. Keller, T. Cassidy, E. Bertino, C. Y. Boquien, R. Buffin, J. Calvo, A. Gaya, C. Gebauer, D. Lamireau, D. Lembo, J. C. Picaud, A. Wesolowska, S. Arslanoglu, L. Cavallarin and M. Giribaldi, *Front. Nutr.*, 2024, **11**, 1409381.
219 J. P. P. Silva, B. C. Bolanho, N. Stevanato, T. B. Massa and C. da Silva, *J. Food Process. Preserv.*, 2020, **44**, e14762.
220 M. Dadan, A. Grobelna, S. Kalisz and D. Witrowa-Rajchert, *Ultrason. Sonochem.*, 2022, **89**, 106156.
221 A. Matys, A. Wiktor, M. Dadan and D. Witrowa-Rajchert, *Foods*, 2021, **10**, 1840.
222 Z. Zhang, M. Nie, Y. Xiao, L. Zhu, R. Gao, C. Zhou, D. Li, Y. Xu and Z. Dai, *LWT*, 2021, **149**, 112052.
223 L. Shaik and S. Chakraborty, *Foods*, 2024, **13**, 1996.
224 E. Radziejewska-Kubzdela, M. Kidoń, A. Kowiel, K. Waszkowiak, K. Szymandera-Buszka, M. Bednarek, M. Kuligowski, J. Kobus-Cisowska and D. Mierzwa, *Molecules*, 2024, **29**, 5586.
225 M. Sayadi, E. Abedi and M. Keramat, *Ultrason. Sonochem.*, 2025, **112**, 107184.
226 G. Ozkan, T. Kostka, G. Dräger, E. Capanoglu and T. Esatbeyoglu, *Food Chem.*, 2022, **380**, 132036.

227 J. Guo, X. Jike, C. Wu, L. Liu, C. Wang, K. Xu, B. Li, H. Xu and H. Lei, *Food Res. Int.*, 2024, **176**, 113803.
228 U. H. Dao, J. N. Lamphun, S. Tongdonyod, S. Taya, S. Phongthai and W. Klangpetch, *Foods*, 2024, **13**, 2995.
229 J. A. Meza-Velázquez, M. Aguilera-Ortiz, J. A. Ragazzo-Sanchez, J. A. R. León, J. R. Minjares-Fuentes and E. A. Luna-Zapién, *Food Sci. Biotechnol.*, 2024, **33**, 1103–1112.
230 I. J. Jiménez-Pulido, D. Rico, D. De Luis and A. B. Martín-Diana, *Foods*, 2024, **13**, 378.
231 M. C. Tenuta, E. Artoni, P. Fava, C. Bignami and F. Licciardello, *Foods*, 2023, **12**(2), 342.
232 A. Dzimitrowicz, P. Jamroz, P. Cyganowski, A. Bielawska-Pohl, A. Klimczak and P. Pohl, *Food Chem.*, 2021, **336**, 127635.
233 S. Akaber, Y. Ramezan and M. R. Khani, *Food Chem.*, 2024, **437**, 137616.
234 A. K. Pour, S. Khorram, A. Ehsani, A. Ostadrahimi and Z. Ghasempour, *Innovative Food Sci. Emerging Technol.*, 2022, **76**, 102945.
235 A. Kyriakoudi, A. Loukri, S. Christaki, Y. Oliinychenko, A. C. Stratakos and I. Mourtzinos, *Food Anal. Methods*, 2024, **17**, 1484–1496.
236 I. P. C. Brito and E. K. Silva, *Food Res. Int.*, 2024, **184**, 114207.
237 S. Carpentieri, G. Ferrari and G. Pataro, *Front. Nutr.*, 2023, **10**, 1158019.
238 S. Belgheisi, A. Motamedzadegan, L. Rashidi, J. M. Milani and A. Rafe, *Food Sci. Nutr.*, 2024, **12**, 8233–8242.
239 L. Boffa, E. Calcio Gaudino, G. Grillo, A. Binello, G. Capaldi, D. Rego, M. Pereira and G. Cravotto, *Foods*, 2024, **13**, 2613.
240 D. Plamada, M. Arlt, D. Güterbock, R. Sevenich, C. Kanzler, S. Neugart, D. C. Vodnar, H. Kieserling and S. Rohn, *Molecules*, 2024, **29**(24), 5849.
241 S. Barut Gök, S. Yıkmış, O. Levent, E. Bozgeyik, K. İlaslan and V. G. Aydın, *ACS Omega*, 2024, **9**, 36699–36709.
242 H. Levent and K. Aktaş, *J. Food Sci.*, 2024, **89**, 2557–2566.
243 G. Che, M. Chen, X. Li, J. Xiao, L. Liu and L. Guo, *Plants*, 2024, **13**, 450.
244 R. Barthwal, A. Negi, D. Kathuria and N. Singh, *Food Chem.*, 2025, **463**, 141489.
245 C. Caner, U. Pala Ç and M. Yüceer, *Food Sci. Technol. Int.*, 2024, 10820132241263198, DOI: 10.1177/10820132241263198.
246 M. Chauhan and P. S. Negi, *J. Food Sci. Technol.*, 2025, **62**, 519–529.
247 B. J. Lee, A. S. Y. Ting and Y. Y. Thoo, *J. Food Sci. Technol.*, 2022, **59**, 979–989.
248 O. Basara and J. Gorzelany, *Molecules*, 2024, **29**, 3616.
249 A. R. A. Silva, M. M. N. Silva and B. D. Ribeiro, *Food Res. Int.*, 2020, **131**, 108972.
250 G. Jia, M. Jiang, A. Sun and Z. Gan, *Molecules*, 2022, **27**, 5892.
251 X. Feng, Z. Zhou, X. Wang, X. Bi, Y. Ma and Y. Xing, *Foods*, 2020, **9**, 218.
252 H. Liu, Y. Xu, S. Zu, X. Wu, A. Shi, J. Zhang, Q. Wang and N. He, *Foods*, 2021, **10**, 1872.
253 Y. Ben-Fadhel, V. Perreault, A. Marciniak, R. Gaillard, Y. Pouliot, G. Brisson and A. Doyen, *J. Food Sci.*, 2024, **89**, 2803–2813.
254 W. Huang, Z. Feng, R. Aila, Y. Hou, A. Carne and A. E. A. Bekhit, *Food Chem.*, 2019, **291**, 253–262.
255 R. Martínez-Beamonte, M. Ripalda, T. Herrero-Continente, C. Barranquero, A. Dávalos, M. C. López de Las Hazas, I. Álvarez-Lanzarote, A. C. Sánchez-Gimeno, J. Raso, C. Arnal, J. C. Surra, J. Osada and M. A. Navarro, *Front. Nutr.*, 2022, **9**, 1065543.
256 S. Yang, S. Li, G. Li, C. Li, W. Li, Y. Bi and J. Wei, *Food Chem.: X*, 2024, **22**, 101372.
257 G. A. Evrendilek, *Food Sci. Technol. Int.*, 2017, **23**, 668–680.
258 N. Bhanu Prakash Reddy, P. Thivya, S. Anandakumar, V. Hema and V. R. N. Sinija, *Food Sci. Technol. Int.*, 2024, 10820132241253301, DOI: 10.1177/10820132241253301.
259 K. Alirezalu, P. E. S. Munekata, O. Parniakov, F. J. Barba, J. Witt, S. Toepfl, A. Wiktor and J. M. Lorenzo, *J. Sci. Food Agric.*, 2020, **100**, 16–24.
260 C. T. Lung, C. K. Chang, F. C. Cheng, C. Y. Hou, M. H. Chen, S. P. Santoso, B. Yudhistira and C. W. Hsieh, *Food Chem.*, 2022, **390**, 133137.
261 U. Roobab, X. A. Zeng, W. Ahmed, G. M. Madni, M. F. Manzoor and R. M. Aadil, *Foods*, 2023, **12**(4), 710.
262 Z. Rosenzweig, A. Martin, C. Hackett, J. Garcia and G. L. Thompson, *ACS Omega*, 2023, **8**, 19833–19842.
263 P. Santiago-Mora, M. Skinner, A. Hendricks, T. Rimkus, B. Meyer, J. Gratzek, S. Pu, L. Woodbury, L. Bond and O. McDougal, *Heliyon*, 2024, **10**, e31790.
264 B. Preeti, M. R. Ravindra, M. Shivaram, D. P. Gajanan and A. M. Singh, *Food Sci. Technol. Int.*, 2024, **30**, 731–740.
265 I. Potoroko, I. Kalinina, V. Botvinnikova, O. Krasulya, R. Fatkullin, U. Bagale and S. H. Sonawane, *Ultrason. Sonochem.*, 2018, **48**, 463–472.
266 P. Khandpur and P. R. Gogate, *Ultrason. Sonochem.*, 2015, **27**, 125–136.
267 J. Wang, Z. Wu and H. Wang, *Ultrason. Sonochem.*, 2022, **86**, 106001.
268 R. Aslam, M. S. Alam, A. Ali, Y. Tao and S. Manickam, *Ultrason. Sonochem.*, 2023, **92**, 106268.
269 B. B. Ismail, D. Liu, Y. Pu, Q. He and M. Guo, *Food Chem.*, 2021, **361**, 130144.
270 Y. Lyu, J. Bi, Q. Chen, X. Wu, M. Gou and X. Yang, *Food Chem.*, 2022, **381**, 132255.
271 X. Cheng, M. Zhang, B. Xu, B. Adhikari and J. Sun, *Ultrason. Sonochem.*, 2015, **27**, 576–585.
272 L. Paniwnyk, *Ultrason. Sonochem.*, 2017, **38**, 794–806.
273 A. Taha, T. Mehany, R. Pandiselvam, S. Anusha Siddiqui, N. A. Mir, M. A. Malik, O. J. Sujayasree, K. C. Alamuru, A. C. Khanashyam, F. Casanova, X. Xu, S. Pan and H. Hu, *Crit. Rev. Food Sci. Nutr.*, 2024, **64**, 6016–6054.
274 L. Astráin-Redín, M. Alejandre, J. Raso, G. Cebrián and I. Álvarez, *Front. Nutr.*, 2021, **8**, 633070.
275 A. Sarker and R. Ali Siddiqui, *Ultrason. Sonochem.*, 2023, **98**, 106533.
276 L. Chen, X. Bi, D. Guo, Y. Xing and Z. Che, *Food Sci. Technol. Int.*, 2019, **25**, 394–403.

 

277 S. Jia, P. Zheng, M. Li, C. Chen, X. Li, N. Zhang, H. Ji, J. Yu, C. Dong and L. Liang, *J. Food Sci.*, 2024, **89**, 6350–6361.
278 X. Wu, W. Zhao, X. Zeng, Q. A. Zhang, G. Gao and S. Song, *Food Sci. Technol. Int.*, 2021, **27**, 441–455.
279 M. M. Nasiru, E. B. Frimpong, U. Muhammad, J. Qian, A. T. Mustapha, W. Yan, H. Zhuang and J. Zhang, *Compr. Rev. Food Sci. Food Saf.*, 2021, **20**, 2626–2659.
280 S. A. Mir, M. W. Siddiqui, B. N. Dar, M. A. Shah, M. H. Wani, S. Roohinejad, G. A. Annor, K. Mallikarjunan, C. F. Chin and A. Ali, *J. Appl. Microbiol.*, 2020, **129**, 474–485.
281 Y. Han, J. H. Cheng and D. W. Sun, *Crit. Rev. Food Sci. Nutr.*, 2019, **59**, 794–811.
282 M. Bayati, M. N. Lund, B. K. Tiwari and M. M. Poojary, *Compr. Rev. Food Sci. Food Saf.*, 2024, **23**, e13376.
283 X. Wei, J. Pandohee and B. Xu, *Crit. Rev. Food Sci. Nutr.*, 2024, **64**, 10121–10137.
284 R. Pandiselvam, S. Barut Gök, A. N. Yüksel, Y. Tekgül, G. Çalişkan Koç and A. Kothakota, *J. Texture Stud.*, 2022, **53**, 800–808.
285 M. B. Traore, A. Sun, Z. Gan, H. Senou, J. Togo and K. H. Fofana, *Can. J. Microbiol.*, 2020, **66**, 125–137.
286 F. Zhu, *Food Chem.*, 2018, **264**, 358–366.
287 E. Sarron, P. Gadonna-Widehem and T. Aussenac, *Foods*, 2021, **10**(3), 605.
288 A. Niveditha, R. Pandiselvam, V. A. Prasath, S. K. Singh, K. Gul and A. Kothakota, *Food Control*, 2021, **130**, 108338.
289 H. Zuo, B. Wang, J. Zhang, Z. Zhong and Z. Tang, *Foods*, 2024, **13**, 2361.
290 M. M. Urugo, T. A. Teka, R. A. Berihune, S. L. Teferi, C. A. Garbaba, J. A. Adebo, H. W. Woldemariam and T. Astatkie, *Innovative Food Sci. Emerging Technol.*, 2023, **85**, 103312.
291 D. Knorr and H. Watzke, *Front. Nutr.*, 2019, **25**(6), 85.
292 EFSA Panel on Biological Hazards, K. Koutsoumanis, A. Alvarez-Ordóñez, D. Bolton, S. Bover-Cid, M. Chemaly, R. Davies, A. De Cesare, L. Herman, F. Hilbert, R. Lindqvist, M. Nauta, L. Peixe, G. Ru, M. Simmons, P. Skandamis, E. Suffredini, L. Castle, M. Crotta, K. Grob, M. R. Milana, A. Petersen, A. X. Roig Sagués, F. Vinagre Silva, E. Barthélémy, A. Christodoulidou, W. Messens and A. Allende, *EFSA J.*, 2022, **20**(3), e07128.
293 S. Park, E. Park and Y. Yoon, *J. Food Prot.*, 2022, **85**, 664–670.
294 A. Pérez-Baltar, A. Alía, A. Rodríguez, J. J. Córdoba, M. Medina and R. Montiel, *Foods*, 2020, **9**, 1092.
295 N. Liang, H. M. H. Mohamed, B. J. Kim, S. Burroughs, A. Lowder, J. Waite-Cusic and D. C. Dallas, *J. Nutr.*, 2023, **153**, 2598–2611.
296 R. Cai, Z. Jing, Y. Li, X. Zhong, Q. Sheng, T. Yue, Z. Wang and Y. Yuan, *Int. J. Food Microbiol.*, 2025, **431**, 111079.
297 C. Kantala, S. Supasin, P. Intra and P. Rattanadecho, *Foods*, 2022, **11**(8), 1102.
298 A. Araújo, C. Barbosa, M. R. Alves, A. Romão and P. Fernandes, *Foods*, 2023, **12**, 3913.
299 C. Delso, A. Berzosa, J. Sanz, I. Álvarez and J. Raso, *Foods*, 2023, **12**, 278.
300 L. J. H. Sweers, M. Mishyna, L. M. Ahrné, R. M. Boom, V. Fogliano, T. Patra, C. M. M. Lakemond and J. K. Keppler, *Curr. Res. Food Sci.*, 2025, **10**, 100940.
301 B. V. Nunes, C. N. da Silva, S. C. Bastos and V. R. de Souza, *Food Bioprocess Technol.*, 2022, **15**, 2185–2209.
302 J. Wang, K. Huang, Z. Wu and Y. Yu, *Ultrason. Sonochem.*, 2022, **82**, 105905.
303 S. Yoon, H. W. Lee, J. J. Bak and S. C. Min, *Int. J. Food Microbiol.*, 2025, **432**, 110912.
304 Ó. Rodríguez, V. Orlien, A. Amin, E. Salucci, F. Giannino and E. Torrieri, *Foods*, 2024, **13**, 3463.
305 J. T. Guimarães, H. Scudino, G. L. Ramos, G. A. Oliveira, L. P. Margalho, L. E. Costa, M. Q. Freitas, M. C. K. Duarte, A. S. Sant'Ana and A. G. Cruz, *Curr. Opin. Food Sci.*, 2021, **42**, 140–147.
306 E. F. Ricciardi, M. A. Del Nobile, A. Conte, F. Fracassi and E. Sardella, *Innovative Food Sci. Emerging Technol.*, 2022, **76**, 102935.
307 Y. Ramezan, H. Hematabadi, M. Ramezan, M. R. Khani, A. Kamkari and A. Najafi Tabrizi, *Food Sci. Technol. Int.*, 2023, **29**, 710–717.
308 J. H. Yoo, K. H. Baek, Y. S. Heo, H. I. Yong and C. Jo, *Food Microbiol.*, 2021, **93**, 103611.
309 M. T. Fernández-Felipe, M. I. Valdez-Narváez, A. Martinez and D. Rodrigo, *Food Res. Int.*, 2024, **193**, 114861.
310 M. I. Valdez-Narváez, M. T. Fernández-Felipe, A. Martinez and D. Rodrigo, *Foods*, 2024, **13**, 2223.
311 Y. Wang, Y. Liu, Y. Zhao, Y. Sun, H. Wang, D. Wang, J. Deng, X. Cui, Z. Ma and R. Dai, *Innovative Food Sci. Emerging Technol.*, 2024, **92**, 103583.
312 Y. E. Kim, G. E. Myung, Y. J. Jeon and S. C. Min, *Food Sci. Biotechnol.*, 2024, **33**, 1633–1640.
313 L.-Z. Deng, A. S. Mujumdar, Z. Pan, S. K. Vidyarthi, J. Xu, M. Zielinska and H.-W. Xiao, *Crit. Rev. Food Sci. Nutr.*, 2020, **60**, 2481–2508.
314 A. Prasad, L. Du, M. Zubair, S. Subedi, A. Ullah and M. Roopesh, *Food Eng. Rev.*, 2020, **12**, 268–289.
315 S.-K. Park, D.-M. Jo, M.-G. Kang, F. Khan, S. D. Hong, C. Y. Kim, Y.-M. Kim and U.-C. Ryu, *J. Photochem. Photobiol., B*, 2021, **222**, 112277.
316 K. Pravallika, S. Pradhan, A. Prabha and S. Chakraborty, *Compr. Rev. Food Sci. Food Saf.*, 2025, **24**, e70107.
317 M. Durán Cassiet, M. L. Kozono, A. Andreone, M. Schenk and S. Guerrero, *Int. J. Food Microbiol.*, 2025, **428**, 110979.
318 A. H. Dasalkar, A. Biswas, S. R. Chaudhari and S. K. Yannam, *Food Chem.*, 2025, **474**, 143120.
319 A. Borges, E. Baptista, T. Aymerich, S. Alves, L. Gama and M. Fraqueza, *LWT*, 2023, **179**, 114641.
320 K.-H. Byun, K. W. Na, M. Ashrafudoulla, M. W. Choi, S. H. Han, I. Kang, S. H. Park and S.-D. Ha, *Food Microbiol.*, 2022, **102**, 103906.
321 Y. Zhang, M. I. Hossain, D. Yeo, T. Niu, S. Hwang, D. Yoon, D. J. Lim, Z. Wang, S. Jung, H. Kwon and C. Choi, *Food Res. Int.*, 2025, **200**, 115454.
322 G. Rojas, P. Esquivel, O. Acosta and J. Usaga, *Food Sci. Technol. Int.*, 2025, 10820132251324685, DOI: 10.1177/10820132251324685.

 

323 Q. Shi, Z. Chen, H. Yan, M. Xu, K. F. Cao, Y. Mao, X. Chen and H. Y. Hu, *Sci. Total Environ.*, 2023, **896**, 165199.
324 M. M. de Souza Grilo, D. W. Schaffner, R. Tavares da Silva, K. L. A. Saraiva, R. S. F. Carvalho, F. Bovo, G. T. de Souza Pedrosa and M. Magnani, *Food Microbiol.*, 2024, **119**, 104453.
325 B. Zai, V. Comacho-Martinez, M. Hasani, L. J. Warriner, T. Koutchma, K. Keener, M. Marcone and K. Warriner, *J. Food Prot.*, 2023, **86**, 100189.
326 Y. A. A. Bernardo and C. A. Conte-Junior, *Adv. Food Nutr. Res.*, 2025, **113**, 65–101.
327 M. Gavahian, C. Sarangapani and N. N. Misra, *Food Res. Int.*, 2021, **141**, 110138.
328 R. Barthwal, A. Negi, D. Kathuria and N. Singh, *Food Chem.*, 2025, **463**, 141489.
329 R. Bocker and E. K. Silva, *RSC Adv.*, 2024, **14**, 2116–2133.
330 C. Zhang, Y. Luo, Z. Deng, R. Du, M. Han, J. Wu, W. Zhao, R. Guo, Y. Hou and S. Wang, *Food Res. Int.*, 2025, **202**, 115701.
331 Q. Xia, Q. Liu, G. I. Denoya, C. Yang, F. J. Barba, H. Yu and X. Chen, *Front. Nutr.*, 2022, **9**, 2022.
332 M. Singla and N. Sit, *Ultrason. Sonochem.*, 2021, **73**, 105506.
333 N. Kalchayanand, J. M. Bosilevac, D. A. King and T. L. Wheeler, *J. Food Prot.*, 2020, **83**, 1520–1529.
334 E. Kontopodi, B. Stahl, J. B. van Goudoever, S. Boeren, R. A. H. Timmermans, H. M. W. den Besten, R. M. Van Elburg and K. Hettinga, *Front. Pediatr.*, 2022, **10**, 828448.
335 Y. A. A. Bernardo and C. A. Conte-Junior, in *Advances in Food and Nutrition Research*, ed. A. S. Sant'ana, Academic Press, 2025, vol. 113, pp. 65–101.