Application of multi-frequency power ultrasound in selected food processing using large-scale reactors: A review

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\textbf{A B S T R A C T}

Ultrasound as an eco-friendly green technology has been widely studied in food processing. Nevertheless, there is a lack of publications regarding the application of ultrasound in food processing using large-scale reactors. In this paper, the mechanisms and the devices of multi-frequency power ultrasound (MFPU) are described. Moreover, the MFPU applied in enzymolysis of protein, and washing of fruits and vegetables are reviewed. The application of MFPU can improve the enzymolysis of protein through modification on enzyme, modification on substrate materials, and facilitation of the enzymatic hydrolysis process. The ultrasound treatment can enhance the removal of microorganisms, and pesticides on the surface of fruits and vegetables. Furthermore, the reactors of ultrasound-assisted enzymolysis of protein, and washing of fruits and vegetables on the industrial scale are also detailed. This review paper also considers future trends, limitations, drawbacks, and developments of ultrasound application in enzymolysis and washing.

1. Introduction

Food processing transforms agricultural produce into ready to eat items for humans through different unit operations. Throughout the processing operations and keeping the product safe for human consumption, processes must be shelf-stable without altering the desired taste, aroma, and delicacy [1]. Modern industrial food processing and preservation started with canning in the eighteenth century, and now the twenty-first century has become the inevitable part of the human food chain. The fundamental food processing operations (heat exchange in different forms and stages, drying, fermentation, packaging, evaporation, mixing, sorting/separation, forming, pumping and others) in different food systems (fruits and vegetables, dairy, meat, and cereals) have become more efficient with the combined technologies and application of computer and information technology [2,3].

The ultrasound technology has transformed food processing manufacturing with its extensive use in numerous processes among the technologies applied in the food processing industry. This sustainable technology itself is a rapid, low-cost, non-thermal, non-destructive technology with many advantages: rapid processes, enhanced process efficiency, elimination of process steps, better quality product and retention of the volatile profile, sensory quality, and aesthetical characteristics of food products, leading to improved shelf-life [4,5]. Traditionally, most food processing unit operations involve applying energy-intensive heat application or chemical treatment to control or inhibit the foodborne pathogens from making food safe for consumption without imparting secondary pollution. Due to the strategic mechanical and/or chemical effect, this novel application of ultrasound in food processing has been proved to be an efficient way to improve shelf-life, remove the microbial load, enhance fermentation output, clean pesticide, and enhance drying rate with better quality and nutrition retention, better emulsification, crystallization, filtration, efficient thawing, and many others [2,6-8].

Different ultrasonic frequency ranges, transducer orientation, and application medium have been used in food industries according to the processing requirements or applicability [7,9]. Historically, single-frequency ultrasonic reactors are commonly used in different ultrasonication, but in recent decades combining different ultrasonic frequencies reported to be more efficient in many food processing applications [1,2,10]. A series of multiple frequencies has been reported

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to be effective and efficient in different unit operations [11-14]. Successful research has led to developing industrial-scale application of multi-frequency power ultrasound on protein enzymolysis, and fruits and vegetables cleaning system at the Institute of Food Physical Processing at Jiangsu University, Zhejiang, China, which will be described below. It has been reported that multi-frequency generator systems have granted benefits because they can produce different cavitation bubble sizes, amplify the numbers of cavitation bubbles, and reduce the thickness of the boundary layer near the adjacent surface [15]. These effects result in the more effective exclusion of smaller particles while cleaning fruits and vegetables. Similarly, these cavitation benefits also help in removing microorganisms [5,16-18], enzymolysis [19-23], protein modification [24-28]. Moreover, a large number of publications mainly focus on the application of ultrasound technology in food processing using lab-scale equipment. The equipment of multi-frequency power ultrasound on large industrial scale is seldom reported.

Therefore, this review article summarizes the current use and possible applications of multi-frequency power ultrasound systems in the selected food processing industry including enzymolysis of protein, and washing of fruits and vegetables, to enhance or improve the efficiency of the unit operations and sketch the potential commercial application for large scale reactors.

2. Background of ultrasound

2.1. Principles of power ultrasound in food processing

When a violinist plays the violin, sound waves are generated through the vibration of the violin’s strings. This sound wave is transmitted to human ears and is called music. In fact, all sound waves are similar to the vibration of the violin. When a violinist plays the violin, sound waves are generated through the vibration of the violin’s strings. This sound wave is transmitted to human ears and is called music. In fact, all sound waves are similar to the vibration of the violin. When a violinist plays the violin, sound waves are generated through the vibration of the violin’s strings. This sound wave is transmitted to human ears and is called music. In fact, all sound waves are similar to the vibration of the violin. When a violinist plays the violin, sound waves are generated through the vibration of the violin’s strings. This sound wave is transmitted to human ears and is called music. In fact, all sound waves are similar to the vibration of the violin. When a violinist plays the violin, sound waves are generated through the vibration of the violin’s strings. This sound wave is transmitted to human ears and is called music. In fact, all sound waves are similar to the vibration of the violin.

Ultrasound is a process of propagation of mechanical vibration in a medium. The effect of ultrasound and medium can be divided into thermal, mechanical and cavitation mechanisms [29]. In the food processing process, ultrasonic waves act on food materials through various physical and chemical effects produced by the mechanisms. The thermal mechanism of ultrasonic waves means that when ultrasonic waves propagate in the medium, their vibration energy is absorbed by the medium and converted into heat energy, which increases the temperature of the medium [30]. The heat generated is directly proportional to the absorption coefficient of the medium, the ultrasonic intensity and duration. The mechanical mechanism of ultrasound means that after ultrasound acts on the medium, the particles in the medium will enter a state of vibration with this mechanical wave, thereby enhancing the movement of the particles in the liquid medium and accelerating the mass transfer [29]. In this process, the propagation form of ultrasonic mechanical energy, the particle displacement, vibration velocity, acceleration and sound pressure of the wave process are all related to the ultrasonic self-effects [31].

The cavitating mechanism of ultrasound is a very complex and important process. Ultrasonic waves propagate in the liquid medium in a cycle of alternating positive and negative pressures. When the ultrasonic intensity is strong enough and under negative pressure, the original integrity structure of the liquid itself will be destroyed, and bubbles will be generated. At this time, the gas initially dissolved in the liquid will enter the bubbles. As time goes by, the bubbles will gradually increase. When the sound pressure becomes positive pressure, it shrinks due to the tension on the bubble surface. At this time, the gas in the bubble enters the liquid. However, as the surface area of the bubble shrinks, the volume of gas diffused into the liquid is reduced. When the next cycle of alternating positive and negative pressure comes, the volume of gas entering the bubble is always higher than that in the returning liquid. After multiple cycles, the volume of the bubble will become larger and larger, until the bubble cannot withstand the pressure of the internal gas and rupture, thereby releasing energy [32]. The effects of bubble growth, contraction, rupture and a series of physical disturbances produced by ultrasonic waves in liquid media are called cavitation effects [33].

The cavitating effect can be divided into stable cavitation and transient cavitation effect according to whether the cavitation bubble bursts or not, [34,35]. The bubbles in the stable cavitation effect will produce a series of acoustic effects when they propagate in the liquid medium. The micro-jet is one of them. The occurrence of micro-jet is due to the violent circular motion of bubbles, which causes vortices to be generated around the bubbles in the liquid medium [36]. The violent disturbance generated by the stable cavity can improve the mass transfer and heat transfer efficiency, and the effect achieved is unmatched by ordinary mechanical stirring [37]. In addition, the stable cavitation effect can induce cell membrane deformation. If the cell is placed in a stable cavitation effect environment, its structure will be destroyed. This is due to the significant velocity gradient difference between the surface of the cavitation bubble and the liquid medium. The unbalanced force produced by this gradient difference causes cell destruction [38].

The transient cavitation effect means that the ultrasonic cavitation bubble will expand rapidly under higher sound pressure [39]. When its volume reaches a critical point, the oscillating frequency of the bubble just coincides with the ultrasonic frequency, the bubbles will burst quickly during the compression stage, and a large amount of energy will be released. The burst of a cavity bubble will generate instantaneous high temperature (above 5000 K) and high pressure (70-100 MPa) around it [40]. Under such instantaneous high temperature and violent pressure changes, it will cause chemical changes both inside the cavity and the liquid medium around the bubble, such as the generation of primary and secondary free radicals [41], the formation of nitrogen dioxide from the interaction between the dissolved nitrogen and oxygen in the medium, causing the decrease of pH [42], and the pyrolysis of organic substances [43,44], etc.

2.2. Application of ultrasound in food processing

Ultrasound has a frequency range of 18 kHz to 10 MHz [45]. According to the frequency range of ultrasonic waves, ultrasonic waves can be divided into high-frequency and low-frequency ultrasound [2]. The frequency of the former ranges over 1 MHz, which is mainly used for food non-destructive testing, quality evaluation, and process control to ensure the quality and safety of food. The frequency of the latter ranges from 18 to 100 kHz, which is mainly used in food processing, such as extraction [46], enzymolysis of protein [11], modification of starch [14], sterilization [47], inactivation of enzymes [48], washing [49,50], osmotic dehydration [13], freezing [51,52] and thawing [53].

Fig. 1 shows the analysis results of ultrasound application in “Food Science Technology”. There were 4068 articles based on the keywords of “Ultrasound, or Ultrasonic, or Sonication” in the web of science (WoS) database (2017 to 2021) with the subject classification “Food Science Technology”. The overlay visualization (Fig. 1A), and the ranking of institutions (Fig. 1B) were obtained using the software VOSviewer (Version 1.6.17) and the WoS system, respectively. As shown in Fig. 1A, extraction, protein, storage, and determination were the main research hotspots in recent five years. The emerging trend of hotspots including protein, shelf life, modification, mechanism, vitro was also shown in the Fig. 1A. The research spots of “ultrasound” and “protein” mainly include extraction, enzymatic hydrolysis, modification, and peptides. Fig. 1B exhibits the ranking of institutions by the number of published papers in “Food science technology”. The Jiangsu University has the most publications (179), followed by Jiangnan University (145), South China University of Technology (91), Islamic Azad University (82), and Zhejiang University (74). Eight institutions of top ten are Chinese.

2.3. Ultrasonic devices

The cavitation effect plays a decisive role in the application of
Ultrasonic wave. Ultrasonic cavitation is a complex physical and chemical process. The formation and collapse of cavitation bubbles depend on ultrasonic parameters, fluid viscosity, system flow rate, gas content, system temperature, and other conditions [54]. Generally, not all cavitation bubbles can generate a significant cavitation effect for ultrasonic cavitation [55]. The bubble nucleus can grow to the cavitation bubble, producing cavitation effect only under selecting suitable conditions. Under this condition, the cavitation bubbles oscillate, grow, contract, and collapse. Then the physical and chemical interactions and extreme physical environment of high temperature and high pressure occur in the tiny space around the cavitation bubble, which provides conditions for the application of ultrasonic in the field of food processing [56-58].

The ultrasonic parameters greatly affecting the cavitation effect mainly include ultrasonic frequency, intensity, ultrasonic transducers’ design. The ultrasonic frequency plays a crucial role in the yield of sonochemical reactions [59]. However, a single-frequency ultrasonic cleaning tank (bath) and ultrasonic cell crusher (probe) are widely used in research work worldwide. There are widespread problems such as excessive ultrasonic power and uneven sound field distribution of sound field caused by standing wave formation, which is far from playing the role of ultrasound in food processing. It seriously restricts the theoretical research, technical development, and industrial application of ultrasonic technology. Ding et al. [55] evaluated the effect of different ultrasonic frequencies (20, 28, 35, 40, and 50 kHz) on the cavitation effect using a numerical simulation model to realize the acoustic field’s distribution visualizing. Fig. 2 showed the acoustic field distribution in the Z direction at frequencies of 20, 28, 35, 40, and 50 kHz. The apparent effects of the standing wave in the acoustic field at every frequency could be observed, resulting in the uneven distribution of the sound field.

Moreover, it was also found that spacing of transducers (Fig. 3A) and arrangement of transducers (Fig. 3B) are two important factors affecting the distribution of sound field [60]. As shown in Fig. 3A, when the spacing of transducers was 25.0 mm and 27.5 mm, the acoustic side...
lobes were less and the acoustic energy was more concentrated. Reducing the spacing of transducers could effectively inhibit the formation of acoustic side lobes. With the increase of transducer spacing, the number of side lobes in the acoustic field increased, and the absolute sound pressure decreased due to the dissipation of sound energy radiation. In addition, the distribution of the sound field became more and more uneven due to the narrowing of the width of the main lobes. The results from Fig. 3B show that no obvious sound pressure distribution law can be observed in the arrangements of transducers under different frequencies. The absolute sound pressures in linear arrangements of transducers for 40 and 50 kHz were higher than others. Circular and ring arrangements of transducers were more likely to produce standing waves, thereby causing the uneven distribution of the sound field. Compared to circular and ring arrangements, the linear and rectangular arrangements exhibited a more even sound field distribution.

In order to solve the poor ultrasonic effect problem and fewer cavitation events resulting from the uneven distribution of sound field, the research team (at the Institute of Physical Food Processing, School of Food and Biological Engineering at Jiangsu University, Zhenjiang, Jiangsu, China.) developed multi-mode multi-frequency power ultrasonic techniques including sweeping and fixed frequency ultrasound, pulse and continuous ultrasound, single- and multi-frequency ultrasound, and multi-frequency ultrasound in sequential and simultaneous working modes. Accordingly, a great many multi-mode multi-frequency power ultrasonic devices have been designed independently (Fig. 4).

3. Application of power ultrasound in enzymolysis of protein

Protein provides the essential amino acids for the growth and metabolism of the human body and has many specific metabolic functions related to physiologically active substances [69]. Nevertheless, many proteins have low bioavailability due to structural defects in their molecules or are rich in anti-nutritional factors, and food processing and heat treatment, which cannot be completely digested and absorbed by the human body. At present, enzymatic hydrolysis is the most commonly used method to improve the functional properties of proteins [67,70]. However, traditional enzymatic hydrolysis technology has shortcomings including low reaction efficiency, long enzymolysis time, low substrate conversion rate, low product activity and product yield [71,72]. Ultrasound technology is widely used in the intensive research of enzymatic hydrolysis reaction due to its advantages of short action time, simple operation, easy control, and low temperature rise [73].

3.1. Ultrasound-assisted enzymolysis in three ways

The main applications of ultrasound in enzymatic hydrolysis focus on three aspects: ultrasonic modification on enzyme [39], ultrasonic modification on substrate materials [74], and ultrasonic treatment on enzymatic hydrolysis process [75].

3.1.1. Ultrasonic modification on enzyme

An enzyme is a protein, and its activity is determined by the state and degree of exposure of the active centre existing on the enzyme molecule. Many biochemical reaction processes can be activated under the application of ultrasound with the participation of enzymes. When ultrasound is applied to the enzyme molecule, the energy released can cause the conformation of the enzyme molecule to change, thereby affecting the change of catalytic activity [39]. Reasonable conformational changes can increase enzyme activity, while irrational or destructive changes reduce enzyme catalytic activity [15].

Generally speaking, the proper intensity of ultrasonic irradiation can make the conformation of the enzyme forward and improve the enzymes’ activity and the substrates’ conversion rate [76]. Ultrasonic treatment under low intensity can increase in the energy of enzyme molecules and the temperature of the medium, causing slight changes in
the conformation of enzyme molecules. This makes the ultrastructure of enzyme molecules more flexible and reasonable, and thus exhibits higher catalytic activity [77]. Nevertheless, under the application of high-intensity ultrasound, the energy of the enzyme molecule is further increased, and the conformation tends to be unreasonable, which causes the catalytic activity of the enzyme molecule to be hindered [70].

The effects of ultrasound on the Alcalase were investigated by Ma et al [66]. It was found that the activity of Alcalase was the highest under the ultrasonic power of 80 W for 4 min. At the ultrasonic parameters, the activity was increased by 5.8% compared to without ultrasound. The mechanism can be attributed to the slight increase in the number of tryptophan on the enzyme surface, an increase in the number of α-helix by 5.2% and a decrease in the number of the random coil by 13.6%. These alterations caused the Alcalase exhibit more regularity and flexibility, which favoured the improvement of Alcalase activity.

Kadkhodae & Povey [78] investigated the effect of ultrasound on the inactivation of Bacillus α-amylase. The results show that ultrasound could lead to protein denaturation, thus enhancing the inactivation of Bacillus α-amylase. The temperature and sonotrode radiating area were the two factors affecting the inactivation rate. The inactivation rate assisted by ultrasound was 24.5 times higher than that without ultrasound application. The mechanism can be attributed to the generation of OH free radicals and shearing force resulting from the ultrasound cavitation effects.

Yang et al [70] studied the extraction effect of peptides from the bovine bone using ultrasound-assisted enzymolysis. The results showed that the extraction yield significantly increased with the ultrasonic power of 1–400 W/L. When the power increased to 800 W/L, the yield of

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**Fig. 3.** Distribution of acoustic field in Z-direction of spacing of transducers in 50 kHz (A), and the arrangements of transducers (B) Spacing between of is 25 mm, 27.5 mm, 30 mm, 32.5 mm, 35 mm, 37.5 mm, 40 mm and 42.5 mm, respectively.
peptides significantly decreased. The triple-helical protein structure was broken and the enzyme structure was destroyed under improper ultrasonic parameters, thereby leading to the enzyme inactivation.

3.1.2. Ultrasonic modification on substrate materials

In addition to the modification of the enzyme, ultrasound pretreatment has been successfully applied to change the structure of substrate materials and improve the substantial enzymolysis efficiency of protein [74]. Many researchers confirmed that ultrasound pretreatment could change the substrate material, making the substrate easier to be enzymatically digested compared to the non-sonication treatment [79-81]. Besides, the ultrasound treatment of protein prior to enzymolysis can facilitate the substantial reaction and promote the release of peptides during enzymatic hydrolysis (Table 1).

Jia et al. [82] reported the effect of mono-frequency ultrasound pretreated defatted wheat germ protein (DGWP) on the enzymatic preparation of ACE-inhibitory peptides. An ultrasonic cell crusher with a flat tip probe (2 cm) at different power levels 0–1800 W was applied. The ultrasound was carried out in mono-frequency mode (20 kHz). Compared to non-ultrasound pretreatment, the average value of apparent breakdown rate constant ($k_A$) of DGWP hydrolysis pretreated by ultrasound increased by 22.2%, and the apparent constant analogous to the Michaelis–Menten constant ($k_M$) decreased by 13.0%. The ACE-inhibitory activity of DGWP hydrolysat increased by 21.0–40.7% after ultrasonic pretreatment, resulting from the release of peptides from DGWP during the process of enzymolysis. In addition, an increase in the surface hydrophobicity of DGWP and disperse in the protein tissue could be observed after ultrasound pretreatment using the ANS fluorescence spectra and SEM analysis. This was in favor of the hydrophobic amino acids release. A similar result was also reported by Zhou et al. [83] in the mono-frequency ultrasound pretreatment of corn gluten meal proteins with the frequency of 20 kHz and a power of 1000 W.

Frequency, power and duration are three important ultrasonic parameters that affect the ultrasonic modification on substrate materials. Ultrasonic frequency has a substantial impact on the efficiency of the sonochemical reaction [84]. Ren et al. [85] comparatively studied the effect of ultrasound pretreatments of zein with different frequencies including sweeping frequency ultrasound (SFU) and fixed frequency ultrasound (FFU) on enzymatic preparations of ACE-inhibitory peptides. Compared to the control, SFU and FFU improved the degree of hydrolysis (DH) by 11%. Nevertheless, there was no significant difference in DH between SFU and FFU. For the ACE-inhibitory activity, SFU and FFU at 22 and 40 kHz were significantly higher than the control, while those at 28 kHz had no significant difference. Moreover, the ACE-inhibitory activity of SFU is greatly higher than that of FFU. The increase in α-helical content (3.4%), and decreases in β-sheet, β-turns, and random coils (24.4%) indicated that SFU pretreatment enhanced the release of ACE-inhibitory peptides from zein by changing the secondary structure and loosening the protein.

Jin et al. [72] investigated the multi-frequency power sweeping ultrasound (MPSU) pretreatment on the kinetics and thermodynamics of corn gluten meal (CGM). The MPSU were sweeping dual-frequency ultrasound (MFPU) pretreatment in different frequencies and working modes on the degree of hydrolysis of rice protein (RP). The MFPU includes mono-, dual- and tri-frequency ultrasound. The latter two MFPU can work in simultaneous and sequential working modes. The results showed that tri-frequency ultrasound in sequential working mode (20/35/50 kHz) had the highest ACE inhibitory activity compared to other ultrasound frequencies and working modes. It indicated that the frequency selection of ultrasound pretreatment of RP is essential for preparing ACE inhibitory peptides.

3.1.3. Ultrasonic treatment on enzymatic hydrolysis process

The reasons why ultrasound can promote the enzymolysis reaction mainly include increasing the contact area by reducing the particle size,
increasing the contact probability between the enzyme and the substrate by enhancing mass transfer, and promoting the effective combination through the influence on the conformation of the enzyme and the substrate [87]. It is challenging to explore the mechanism of ultrasound irradiation promoting enzymolysis efficiency because the action system mixes with enzymes, proteins and hydrolysates [15]. An immobilized enzyme can be applied to investigate the mechanism, as it can be separated out from the system after enzymolysis [75].

Wang et al. [15] used sweeping dual-frequency ultrasound (SDFU) to promote enzymolysis on rapeseed protein by immobilized Alcalase. The DH increased by 75.38% with SDFU assisted-enzymolysis under the optimal parameters. The yield of protein, peptides and total sugar in the hydrolysate increased by 64.61%, 40.88% and 23.60%, respectively. The decrease in α-helix (10.7%) and random coil content (4.5%), and increase in the β-chain (2.4%) indicated the change in the secondary structure of the enzyme after ultrasound treatment from the analysis of CD. The SEM also exhibited that ultrasound treatment increased the degree of surface roughness of Alcalase. It can be concluded that the improvement of hydrolysis by DFU assisted-enzymolysis was achieved by enhancing the solid solubility, changing the molecular structure of protein and increasing the surface area of the immobilized enzyme.

In summary, ultrasound can improve the efficiency of enzymatic hydrolysis from three aspects: enzyme processing, substrate processing, and enzymatic hydrolysis processing. Whether the ultrasound promotes or inhibits the enzymatic hydrolysis reaction of protein is affected by various factors such as enzyme types and characteristics, ultrasonic parameters including power, frequency, and durations. Therefore, choosing the appropriate ultrasound parameters is the key to promoting the enzymatic hydrolysis reaction [88].

| Sample matrix                  | US devices | US conditions | Main Results                                                                 | Ref./Year |
|--------------------------------|------------|---------------|-------------------------------------------------------------------------------|-----------|
| Oat-Isolated Protein           | Fig. 1A    | Frequency: 20 kHz; Power: 250-1250 W. | Under the best conditions of ultrasound pretreatment, the hydrolysis rate and the ACE inhibitory activities of peptides were significantly (< 0.001) increased by 32.1 and 53.8 %, respectively compared to the samples without ultrasound pretreatment. | [98]/2015 |
| Wheat gluten (WG)              | Fig. 1A    | Frequency: 20 kHz; Power density: 200 W/L. | The decrease in α-helix (10.7%) and random coil content (4.5%), and increase in the β-chain (2.4%) indicated the change in the secondary structure of the enzyme after ultrasound treatment from the analysis of CD. | [99]/2015 |
| Sodium caseinate (NaCas)       | Fig. 1A    | Frequency: 20, 28, 35, 40, and 50 kHz; Power density: 0-500 W/L. Modes: Mono-frequency | Ultrasound significantly (p < 0.05) increased the degree of hydrolysis (DH), conversion rates of protein, ACE inhibitory. Ultrasound successfully improved enzymolysis of NaCas and release more ACE inhibitory activity due to the increases in specific surface area of protein molecule. | [100]/2017 |
| Rapesed protein (RP)           | Fig. 1B    | Frequency: 22, 28, 33, 40, and 68 kHz; Power density: 20-70 W/L; Modes: Mono- and Dual-frequency | After DFU assisted-enzymolysis, the yield of soluable solids content, including protein, peptides and total sugar in hydrolysate increased by 64.61%, 40.88% and 23.60%, respectively. The DH increased by 74.38% with DFU assisted-enzymolysis. | [15]/2016 |
| Defatted wheat germ protein (DWGP) | Fig. 1B    | Frequency: 22, 28, 33, 40, and 68 kHz; Power: each was 600 W; Power density: 40–100 W/L; Modes: Mono-, and Dual-frequency | Under the dual-fixed frequency ultrasound mode of 28/40 kHz, the ACE inhibitory activity of DWGP hydrolysate was the highest with its value of 74.75% (increased by 62.30% compared to control). | [101]/2017 |
| Zein protein                   | Fig. 1B    | Sweeping frequency: 40 ± 2 kHz; Power density: 100 W/L; Modes: Mono-frequency | Ultrasound pretreatment significantly increased the degree of hydrolysis (DH) of zein and the ACE-inhibitory activity of zein hydrolysates by 19.37 and 133.76%, respectively. | [102]/2017 |
| Rapesed protein                | Fig. 1C    | Frequency: 20, 28, 35, and 50 kHz; Power density: 150-200 W/L. Modes: Mono-, and Dual-frequency | Sequential dual-frequency ultrasound (SDSU) pretreatment remarkably increased rapeseed protein enzymolysis efficiency compared to the samples without SDFU pretreatment. This higher efficiency of enzymolysis was attributed to the significant decrease in the kinetic and thermodynamic parameters k and k. | [103]/2018 |
| Rapesed meal protein concentrate | Fig. 1C    | Frequency: 20, 28, 35, and 50 kHz; Power density: 150-200 W/L. Modes: Mono-, and Dual-frequency | Ultrasound could be considered as a promising pretreatment method for preparing enzymatic hydrolysates with high bioavailability and thus realize the maximum utilization of rapeseed meal protein. | [67]/2021 |
| Sunflower-meal protein (SMP)   | Fig. 1C    | Frequency: 20, 28, 35, and 50 kHz; Power density: 220 W/L. Modes: Mono-, and Dual-frequency | Ultrasonication could facilitate the releasing/unfolding of hydrophobic amino acids from SMP over nonsonicated samples during enzymolysis with high antioxidative capacity. | [104,105]/2018, 2019 |
| Rice protein (RP)              | Fig. 1D    | Frequency: 20, 28, 35, 40 and 50 kHz; Power: each was 300 W; Power density: 100 W/L; Modes: Mono-, Dual- and Tri-frequency. | Dual-frequency ultrasound pretreatment enhanced SMP: enzyme efficiency at different substrate and enzyme concentrations, temperature, and pH. | [86]/2017 |
| Corn gluten meal (CGM)         | Fig. 1E    | Frequency: 20, 23, 25, 28, 35, and 40 kHz; Power density: 100 W/L. Modes: single-, triple-, quadruple, quintuple and sextuple frequency. | With a sequential duple-frequency of 20/40 kHz showing the most significant effect, the maximum value of enzymolysis efficiency and protein dissolution rate were 15.99% and 61.69%, respectively. | [106]/2021 |
| Corn gluten meal (CGM)         | Fig. 1F    | Frequency: 20 (fundamental one), 23, 25, 28, 35, and 40 kHz; Power density: 60–200 W/L. Modes: Dual-frequency | Ultrasoundication had considerable effect on the conformation of CGM and consequently improved the susceptibility to alcalase proteolysis. | [107]/2020 |
3.2. Reactors of ultrasound-assisted enzymolysis of protein on the industrial scale

The industrial-scale continuous multi-frequency power ultrasonic equipment for enzymolysis of protein at the Institute of Food Physical Processing, School of Food and Biological Engineering (Jiangsu University, Zhenjiang, Jiangsu, China) shown in Fig. 5 was built in 2018. This processing line includes the anterior and back-end process. The former is comprised of an enzymatic hydrolysis tank, continuous membrane reactor, and dual-frequency ultrasonic reactor. The latter includes filtration, vacuum concentration, and spray drying. The enzymatic hydrolysis tank can be loaded with 500 L. During the enzymatic hydrolysis process, the pH of the reaction mixture is automatically controlled by a regulator. The tank is connected to the membrane reactor and ultrasonic reactor. The mixture can be treated by dual-frequency ultrasonic in the sequential or simultaneous working mode under the frequency of 20 and 40 kHz and the power level of 2 kW. According to the time of enzyme adding, the reaction can be divided into ultrasonic modification on substrate materials and ultrasonic treatment on enzymolysis process. Then the mixture will be pumped to the continuous membrane reactor. The mixture with a small particle size will pass through the membrane and go to the next unit, while that with a big particle size that can not pass the membrane will flow back to the tank. The filtration line can be divided into micro-, ultra-, and nano-filtration. The proper filtration line will be selected according to the terminal desired particle size of the enzymolysis liquid. After filtration, the vacuum concentration and spray drying will carry out to obtain the final powder products. Since the reactor was built, it was successfully applied to produce peptides from rapeseed protein, wheat gluten, defatted wheat germ protein, zein protein, rice protein (RP), and donkey-hide gelatin, etc.

4. Application of power ultrasound in the washing of fruits and vegetables

4.1. Ultrasound-assisted washing

Ultrasound-assisted washing has been successfully adopted in small- to medium-scale cleaning of fruits and vegetables, metal parts, glasses, plastics, medical tools, jewellery, and laboratory equipment. Nowadays, domestic use ultrasound-assisted vegetable cleaners can be purchased from the market. The enhancement process is principally triggered by cavitation, where strong convective currents, acoustic streaming, and sediment, microorganism, and pesticide. The multi-frequency power ultrasonic equipment for cleaning fruits and vegetables at the Institute of Food Physical Processing, School of Food and Biological Engineering (Jiangsu University, Zhenjiang, Jiangsu, China) shown in Fig. 5 was built in 2019. Fig. 6A shows the multi-frequency power ultrasonic conveyor belt cleaning equipment. The production capacity of this equipment for leafy vegetable is over 2000 kg/h. Six ultrasonic vibration boxes with different frequencies (20, 28, 35, 40, 50, and 66 kHz) are placed at the bottom of the cylindrical tank. The transducers are arranged evenly in the box and the power of each box is 2 kW. It can operate under multifrequency multi-mode ultrasound controlled by PLC. This equipment can be applied to the root, stem, leafy vegetables, and fruits to remove sediment, microorganism, and pesticide. The multi-frequency power ultrasonic centrifugal cleaning equipment is shown in Fig. 6B. Six arc-shaped ultrasonic vibration boxes with different frequencies (20, 28, 35, 40, 50, and 66 kHz) are placed at the bottom of the cylindrical tank. During the washing process, the basket with fruits and vegetables can be put inside the equipment. The sediment, microorganism, and pesticide can be removed through centrifugal forces and ultrasonic treatment. This equipment is especially suitable for washing fragile leafy vegetables, such as lettuce, Chinese green vegetables, and chives.

4.2. Reactors of ultrasound-assisted washing of fruits and vegetables on the industrial scale

The industrial-scale multi-frequency power ultrasonic equipment for cleaning fruits and vegetables at the Institute of Food Physical Processing, School of Food and Biological Engineering (Jiangsu University, Zhenjiang, Jiangsu, China) shown in Fig. 5 was built in 2019. Fig. 6A shows the multi-frequency power ultrasonic conveyor belt cleaning equipment. The production capacity of this equipment for leafy vegetable is over 2000 kg/h. Six ultrasonic vibration boxes with different frequencies (20, 28, 35, 40, 68, and 80 kHz) are placed in series on the conveyor belt cleaning tank. The transducers are arranged evenly in the box and the power of each box is 2 kW. It can operate under multifrequency multi-mode ultrasound controlled by PLC. This equipment can be applied to the root, stem, leafy vegetables, and fruits to remove sediment, microorganism, and pesticide. The multi-frequency power ultrasonic centrifugal cleaning equipment is shown in Fig. 6B. Six arc-shaped ultrasonic vibration boxes with different frequencies (20, 28, 35, 40, 50, and 66 kHz) are placed at the bottom of the cylindrical tank. During the washing process, the basket with fruits and vegetables can be put inside the equipment. The sediment, microorganism, and pesticide can be removed through centrifugal forces and ultrasonic treatment. This equipment is especially suitable for washing fragile leafy vegetables, such as lettuce, Chinese green vegetables, and chives.

5. Conclusion and future trends

Many researchers have been working on ultrasonic technology in food processing for many years and it is found that ultrasound is an advanced eco-friendly non-thermal technology. This paper reviewed the fundamental principles of ultrasound for food processing and the influences of multi-frequency power ultrasound (MFPU) treatment on the enzymolysis of protein, and washing of fruits and vegetables. The literature showed that MFPU pretreatment improved the enzymatic hydrolysis of protein, and facilitated the washing of fruits and
vegetables. Meanwhile, the reactors of ultrasound-assisted enzymolysis of protein and washing of fruits and vegetables were also exhibited. It should be emphasized that several drawbacks limit the development of ultrasound-assisted enzymolysis of protein and washing of fruits and vegetables, which were listed as follows:

For the research on improving the enzymolysis characteristics of the ultrasonic pretreatment of protein, most of the work focused on the activity changes of the proteolysis products before and after the ultrasonic pretreatment and the corresponding changes in the structure of the protein substrate. There are still some shortcomings in controlling the process of ultrasonic pretreatment and functional evaluation of products, mainly including:

(1) There is a lack of monitoring of protein structure and activity of enzymatic hydrolysis products during ultrasonic pretreatment, and information on the dynamic changes of various indicators of protein structure during ultrasonic pretreatment. In addition, which protein has the greatest impact on enzymatic hydrolysis products, and the relationship between the various structural changes are still unclear. The specific quantitative relationship between the degree of protein denaturation and the improvement of its enzymatic properties is still unclear.

(2) For the process control and parameter optimization of peptides prepared by enzymatic hydrolysis, the methods of time-sharing sampling and ex-situ determination are still used. It requires cumbersome procedures such as sampling from the reactor, enzyme inactivation, and centrifugation. The workload is extensive and accurate results cannot be obtained because the reaction site is left, and in-situ monitoring cannot be achieved. To establish the in-situ intelligent monitoring system for enzymatic hydrolysis process and ultrasonic pretreatment process, it is necessary to develop the corresponding software system and intelligent instrument control system based on the established spectral prediction model, which can be applied to the in-situ spectral instrument to realize intelligent control of the terminal of enzymatic hydrolysis.

(3) The peptide products from different varieties of substrate materials and with different molecular weights after ultrasonic enzyme hydrolysis determine their functional properties, physiological activity, and bioavailability, such as improving immunity, anti-cancer, fall blood pressure, lipid-lowering, and anti-ageing diseases. The physiological activity and bioavailability of peptides from different varieties of substrate materials by different ultrasonic treatments needed to be investigated and evaluated in the future.

Most research on improving the washing effect focus on removing pesticides, loosely attached dirt or foreign material, and microorganisms before and after the ultrasonic treatment. There are still some drawbacks in ultrasonic washing, mainly including:

(1) In the washing processing of fresh-cut vegetables, especially leafy vegetables, ultrasound irradiation can destroy the tissue and cells of leafy vegetables, which affects the integrity of the vegetable shape. Thus, specific studies on optimizing ultrasonic parameters for each leafy vegetables need to be carried out.

(2) During industrial ultrasound manufacturing, triggered noise can be hazardous to the auditory system of line workers, especially when exposed to it frequently. Therefore, overall noise levels must be maintained at levels acceptable to human hearing systems, which may increase the cost of ultrasound equipment.

(3) The establishment cost for new technology is a big challenge from the economic and technical perspectives.

CRediT authorship contribution statement

Baoguo Xu: Conceptualization, Writing – review & editing. S.M. Roknul Azam: Conceptualization, Writing – review & editing. Min Feng: Writing – review & editing. Bengang Wu: Writing – review & editing. Weiqiang Yan: Writing – review & editing. Cunshan Zhou: Supervision. Haile Ma: Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial
| Mode of Ultrasound                          | Objective                                                                 | Effects of ultrasound and recommendation                                                                 | Reference |
|-------------------------------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|-----------|
| Pulsed electric field and ultrasound      | Microbial load and bioactive compounds of grapefruit juice                | Reduced microbial load as combined pulsed electric fields (PEF) with ultrasound. Improved the antioxidant activity, total phenolics, flavonoids, flavonoids, lycopene, and total carotenoids. PEF + ultrasound also improves the quality of grapefruit juice and has the potential for industrial scale. | [108]     |
| Ultrasound-assisted extraction             | Extraction and determination of pesticides in fruit and vegetable.        | Due to the application of ultrasound, the relative recovery ranged improved.                              | [109]     |
|                                           |                                                                           |                                                                                                          | [110]     |
|                                           |                                                                           |                                                                                                          | [111]     |
| Combined ultraviolet and ultrasound treatments | Design of modern pasteurization methods                                  | The integration of ultraviolet and ultrasound processes into the pasteurization process limits microbial activity at lower temperatures and time than the conventional pasteurization process. | [112]     |
| Ozone and ultrasound                       | Effect of ultrasound in disinfecting and decontaminating strawberry       | A positive effect of ozone with ultrasound on disinfecting and decontaminating with extended shelf-life.   | [113]     |
| Frequency-based ultrasound                 | Effect of multi-frequency based ultrasound on the removal efficiency and impact of ultrasound on leafy vegetable cleaning. |                                                                                                          |           |
| Ultrasound with electrolyzed water        | Effects of ultrasound and dipping in electrolyzed water on quality and shelf life of the refrigerated chicken breast | Sonication for 30 min increased the tenderness of the samples. The combination of ultrasound and acidic electrolyzed water treatment reduces microbial counts without changing the lipid oxidation and color parameters. | [114]     |
| Ultrasound and malic acid treatment        | Compare the impact of ultrasound in inactivating Salmonella typhi,        | The combination of US treatment and 1% malic acid reduced the initial bacterial load.                      | [115]     |

### Table 2 (continued)

| Mode of Ultrasound                        | Objective                                                                 | Effects of ultrasound and recommendation                                                                 | Reference |
|-------------------------------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|-----------|
| Ultrasound with steam                     | Removal of surface contaminants from fruits, vegetables, and meats.       | Short-time heating with ultrasound lowers the microbial (E. coli) load.                                | [116]     |
| Ultrasound and 80 ppm nisin-ultrasound    | Ultrasound on total aerobic bacteria, yeast, and mold; physical and nutritional quality of fresh carrot juice. | Nisin-assisted ultrasound has the best result in hindering total aerobic bacterial. Ultrasound had no apparent effect on the yeast and mold in the studied condition. Nisin-assisted ultrasound also retained the best product quality. Ultrasound-assisted method reduced microbial load significantly, improved shelf-life with the best product quality of the dry-cured ham. | [117]     |
| Low-intensity electrical current and ultrasound | Effect of studied methods on reduction of pesticide residues from lettuce | 1400 mA and ultrasound (24 kHz) at 10 min could remove 92.57, 81.99 and 93.09% of captan, thiamethoxam and metalaxyl residues. Based on the synergistic effect of combining low-intensity electrical current and ultrasound, it has been proposed that the studied method has a great potential for industrial scale application for removing pesticides from vegetables. | [94]      |
| Airborne ultrasound                       | Effect of airborne ultrasound on microbial inactivation and physicochemical properties. | Airborne acoustic technology is an effective technology for microbial inactivation with the most negligible impact on product quality. For the ultrasound treated sample, the polypeptide chain expanded and gelling properties significantly improved. | [120]     |
|                                          | Airborne ultrasound                                                      |                                                                                                          |           |
|                                          | Airborne ultrasound                                                      |                                                                                                          |           |

(continued on next page)
| Mode of Ultrasound | Objective                                                                 | Effects of ultrasound and recommendation                                                                 | Reference |
|-------------------|---------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|-----------|
| Ultrasound (40 kHz) | Effect of ultrasound on the physicochemical characteristics of cherry tomatoes. | with a regular and uniform network. Silver nanoparticles with ultrasound significantly reduced microbial load without affecting quality parameters. Sonication for 6 min enhanced the apparent viscosity and consistency, reducing tyramine and total biogenic amine. | [123]     |
| Ultrasound (20 kHz) | Effect of ultrasound on probiotic goat milk yogurt                        | Ultrasound and high-power ultrasound combined with carbon dots coating successfully improves microbial and product quality with the best flavor profile. | [124]     |
| Ultrasound-assisted matrix solid-phase dispersion | pesticide extraction from fruits and vegetables                           | An efficient, simple, cheap, robust, and environmentally friendly ultrasound-assisted method was developed for extracting different pesticides. | [125]     |
| Ultrasound combined with carbon | Effect of ultrasound with carbon dots coating on the microbial and physicochemical quality of fresh-cut cucumber. | Ultrasound treatment combined with carbon dots coating successfully improves microbial growth and reduced weight loss, firmness, total soluble solids, and color change. | [126]     |
| Ultrasound (20 kHz) | Ultrasound treatment on microbial loads and the quality of modified atmospheric packed fresh-cut cucumber. | Ultrasound treatment for 10 min inhibited microbial growth and reduced weight loss, firmness, total soluble solids, and color change. | [127]     |
| High-intensity ultrasound | Effect of ultrasound on microbial transglutaminase-catalyzed tofu gel | The application of ultrasound improved the water holding capacity and a dense, homogenous, and stable network structure. | [128]     |
| Pulsed electric field and high-power ultrasound | Effect of ultrasound and Pulsed electric field combined method on E. coli, A. niger and B. pumilus, | Studied method inactivated vegetative bacteria or fungal spores in emulsions with limited inactivation for bacterial spores. The optimal condition could improve beverage kinetic stability, avoid phase separation, and decrease particle size and denaturation of whey proteins. | [129]     |
| High-intensity ultrasound (0, 200, 400 and 600 W) | Effect of different ultrasonic power levels on microbial inactivation on prebiotic whey beverage. | Nonthermal sterilization of mango juice with regards to microbial growth and quality changes. | [130]     |
| Ultrasound and warm water | Ultrasound-assisted warm water treatment for kale seeds to inactivate microorganisms. | Ultrasound-assisted warm water treatment significantly reduced the E. coli counts in the seeds. The germination rates of the samples were above standard. | [131]     |
| Ultrasound (20, 40, and 60 kHz) | Ultrasound-assisted treatment for ultrafiltered feta-type cheese | Microbial load (E. coli, S. aureus, P. chrysogenum, and C. sporogenes) reduced and improved the acidity of ripened cheese. | [132]     |
| Pulsed electric field and high-power ultrasound | Effect of ultrasound and Pulsed electric field combined method on E. coli, A. niger and B. pumilus, | Studied method inactivated vegetative bacteria or fungal spores in emulsions with limited inactivation for bacterial spores. The optimal condition could improve beverage kinetic stability, avoid phase separation, and decrease particle size and denaturation of whey proteins. | [129]     |
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| Ultrasound (20, 40, and 60 kHz) | Ultrasound-assisted treatment for ultrafiltered feta-type cheese | Microbial load (E. coli, S. aureus, P. chrysogenum, and C. sporogenes) reduced and improved the acidity of ripened cheese. | [132]     |
| Ultrasound (40 kHz) | Effect of ultrasound on the physicochemical characteristics of cherry tomatoes. | with a regular and uniform network. Silver nanoparticles with ultrasound significantly reduced microbial load without affecting quality parameters. Sonication for 6 min enhanced the apparent viscosity and consistency, reducing tyramine and total biogenic amine. | [123]     |
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| High-intensity ultrasound (0, 200, 400 and 600 W) | Effect of different ultrasonic power levels on microbial inactivation on prebiotic whey beverage. | Nonthermal sterilization of mango juice with regards to microbial growth and quality changes. | [130]     |
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interests or personal relationships that could have appeared to influence
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References

[1] R.P.F. Guine, S.G. Floreenca, M.J. Barroca, O. Anjos, The duality of innovation and
food development versus purely traditional foods, Trends in Food Science &
Technology 109 (2021) 16–24.

[2] N. Bhargava, R.S. Mor, K. Kumar, V.S. Sharanagat, Advances in application of
ultrasound in food processing: A review, Ultrasoundics Sonochemistry 70 (2021),
105293.
ultrasonic sonochemistry 81 (2021) 105855
B. Xu et al.

[27] B.K. Mintah, R. He, M. Dabbour, J. Xiang, A.A. Agyekum, H. Ma, Techno-

[26] C. Wen, J. Zhang, H. Zhang, Y. Duan, H. Ma, X. Luo, Advances in ultrasound assisted extraction of bioactive compounds from cashew crops – A review, Ultrasonics Sonochemistry 48 (2018) 538–549.

[19] F. Zhang, Z. Zhu, D.-W. Sun, Using power ultrasound to accelerate food freezing processes: Effect on freezing efficiency and food microstructure, Critical Reviews in Food Science and Nutrition 58 (2018) 2842–2853.

[17] listeria innocua in fresh-cut Chinese cabbage by a combined washing treatment of sweeping frequency ultrasound and sodium hypochlorite, LWT - Food Science and Technology 101 (2019) 410–418.

[15] J. Zhu, Multi-frequency multi-mode ultrasound treatment for removing pesticides from lettuce (Lactuca sativa L.), in: and effects on product quality, LWT - Food Science and Technology 59 (2019), 104712.

[13] B. Xu, J. Chen, E. Sylvain Tiliwa, W. Yan, S.M. Roknul Azam, J. Yuan, B. Wei, S. Li, R. Zhang, D. Lei, Y. Huang, S. Cheng, Z. Wu, G. Cravotto, Impact of ultrasound pretreatment on the structure of watermelon seed protein and the antioxidant activity of its hydrolysates, Food Chemistry 299 (2019), 125165.

[10] S. Li, R. Zhang, D. Lei, Y. Huang, S. Cheng, Z. Zhu, Z. Wu, G. Cravotto, Impact of ultrasound, microwaves and high pressure processing on food components and their interactions, Trends in Food Science & Technology 109 (2021) 1–15.

[8] Y.Y. Wang, J.K. Yan, Y. Ding, H. Ma, Effects of ultrasound on the thawing of quick-frozen small yellow croaker (Larimichthys polyactis) based on TMT-labeled quantitative proteomic, Food Chemistry 366 (2022), 130600.

[6] J. Chandrapala, C. Oliver, S. Kentish, M. Ashokkumar, Ultrasonics in food processing: A review, Ultrasonics Sonochemistry 70 (2021), 105325.

[5] S.M.R. Azam, H. Ma, B. Xu, S. Devi, S.L. Stanley, M.A. Bakar Siddique, S.M. Roknul Azam, H. Ma, B. Xu, J. Chen, E. Sylvain Tiliwa, W. Yan, S.M. Roknul Azam, J. Yuan, B. Wei, S. Li, R. Zhang, D. Lei, Y. Huang, S. Cheng, Z. Wu, G. Cravotto, Impact of ultrasound pretreatment on the structure of watermelon seed protein and the antioxidant activity of its hydrolysates, Food Chemistry 299 (2019), 125165.

[4] E.R. G, Ultrasound: a new opportunity for food preservation, Blackie Academic and Professional, London, 1998.

[3] J. Chen, M. Zhang, B. Xu, J. Sun, Z. Gao, Infusion of CO2 in food processing: Effect of multiple mode sonochemical pretreatment on the quantitative proteomic, Food Chemistry 366 (2022), 130600.

[2] B. Bhandari, J. Zhu, Efficacy of ultrasound treatment in the removal of pesticide residues from fresh vegetables: A review, Trends in Food Science & Technology 79 (2020) 109–113.

[1] F.J. Toublan, S. Boppart, K.S. Suslick, Tumor targeting by surface-modified protein microspheres, Journal of the American Chemical Society 128 (2006) 6540–6541.
bioactive compounds and microbial quality of grapefruit juice, Journal of Food Processing and Preservation 42 (2018).

[109] L. Abdi Jamil, H. Zeyad Sami, A. Ali, M. Soleymyan, A. Soraya, Combination of modified ultrasound-assisted extraction with continuous sample drop flow microextraction for determination of pesticides in vegetables and fruits, Microchemical Journal 160 (2021) 105692.

[110] Z. Aladaglo, A.R. Fakhari, S.I. Alavioon, M. Dabiri, A mesoporous nanosorbent composed of silica, graphene, and palladium (II) for ultrasound-assisted dispersive solid-phase extraction of organophosphorus pesticides prior to their quantitation by ion mobility spectrometry, Microchimica Acta 187 (2020).

[111] Z. Aladaglo, A.R. Fakhari, A. Shashami, Magnetic MWCNT@gudniine acetic acid@Cu as a nanosorbent for ultrasound assisted dispersive magnetic solid phase extraction of heterocyclic pesticides in citrus samples, Journal of the Iranian Chemical Society (2021).

[112] T.A.M. Alabdali, N.C. Icyer, G.U. Ozkaya, M.Z. Durak, Effect of Stand-Alone and Combined Ultraviolet and Ultrasound Treatments on Physicochemical and Microbial Characteristics of Pomegranate Juice, Applied Sciences-Basel 10 (2020).

[113] M. Ayenha, A. Raheel, A. Ullah Malik, M.I. Ur Raheem, A. Sattar Khan, M. Ul Hasen, H. Zahoor, S. Zarghona, Combined aqueous ozone and ultrasound application inhibits microbial spoilage, reduces pesticide residues and maintains storage quality of strawberry fruits, Journal of Food Measurement and Characterization 15 (2021) 1437–1451.

[114] A.S. Babaoglu, H.B. Pocan, T. Demirci, M. Karakaya, Ultrasound application and electrolyzed water treatment improve the microbial quality and textural parameters of chicken breast meats, Journal of Food Safety and Food Quality/Archiv fuer Lebensmittelhygiene 72 (2021) 12–20.

[115] S.M. Bagher Hashemi, J. Dornoush, Ultrasound and malic acid treatment of sweet lemon juice: microbial inactivation and quality changes, Journal of Food Processing and Preservation 44 (2020) e14866.

[116] R. Basumatry, H. Vatankhah, M. Dwiwedi, D. John, H.S. Ramaswamy, Ultrasound-steam combination process for microbial decontamination and heat transfer enhancement, Journal of Food Process Engineering 43 (2020).

[117] X. Bi, Z. Zhou, X. Wang, X. Jiang, L. Chen, Y. Xing, Y. Che, Changes in the Microbial Content and Quality Attributes of Carrot Juice Treated by a Combination of Ultrasound and Nisin During Storage, Food and Bioprocess Technology 13 (2020) 1556–1565.

[118] R.I. Castillo-Zamudio, I. Paniagua-Martinez, C. Ortuno-Cases, M.A. Garcia-Alvarado, V. Larrea, J. Benedito, Use of high-power ultrasound combined with supercritical fluids for microbial inactivation in dry-cured ham, Innovative Food Science & Emerging Technologies 67 (2021).

[119] M.F. Cenje, M. Baslar, O. Babuncelb, M. Kiliçli, Reduction of pesticide residues from tomatoes by low intensity electrical current and ultrasound applications, Food Chemistry 267 (2018) 60–66.

[120] C.M.G. Charroux, C.P. O’Donnell, B.K. Tivari, Effect of airborne ultrasonic technology on microbial inactivation and quality of dried food ingredients, Ultrasonics Sonochemistry 56 (2019) 313–317.

[121] Q. Cui, G. Wang, D. Gao, L. Wang, A. Zhang, X. Wang, N. Xu, L. Jiang, Improving the gel properties of transgenic microbial transglutaminase cross-linked soybean-whey mixed protein by ultrasonic pretreatment, Process Biochemistry 91 (2020) 104–112.

[122] Q. Cui, X. Wang, G. Wang, R. Li, X. Wang, S. Chen, J. Liu, L. Jiang, Effects of ultrasound treatment on the gel properties of microbial transglutaminase crosslinked soy, whey and soy-whey proteins, Food Science and Biotechnology 28 (2019) 1455–1464.

[123] J.F.B. De Sao Jose, H.S. Medeiros, N.J. De Andrade, A.M. Ramos, M.C.D. Vanetti, Effect of Ultrasound and Chemical Compounds on Microbial Contamination, Physicochemical Parameters and Bioactive Compounds of Cherry Tomatoes, Italian Journal of Food Science 30 (2018) 467–486.

[124] K. Delgado, O. Vieira, I. Dammak, F. Frasso, A. Brigida, M. Costa, C. Conte-Junior, Different Ultrasound Exposure Times Influence the Physicochemical and Microbial Quality Properties in Probiotic Goat Milk Yogurt, Molecules 25 (2020).

[125] E.O. dos Santos, J.O. Gonzales, J.C. Ores, L.C. Marube, S.S. Caldan, E.B. Furlong, E.G. Primel, Sand as a solid support in ultrasound-assisted MSPD: A simple, green and low-cost method for multiresidue pesticide determination in fruits and vegetables, Food Chemistry 297 (2019).

[126] K. Fan, M. Zhang, H. Chen, Effect of Ultrasound Treatment Combined with Carbon Dots Coating on the Microbial and Physicochemical Quality of Fresh-Cut Cucumber, Food and Bioprocess Technology 13 (2020) 648–660.

[127] K. Fan, M. Zhang, F. Jiang, Ultrasound treatment to modified atmospheric packaged fresh-cut cucumber: Influence on microbial inhibition and storage quality, Ultrasonics Sonochemistry 54 (2019) 162–170.

[128] H. Gao, J. Xu, M. Tan, D. Mu, X. Li, Y. Zhao, Z. Zheng, Effects of high-intensity ultrasound soymilk pretreatment on the physicochemical properties of microbial transglutaminase-catalyzed tofu gel, Journal of Food Science 86 (2021) 2410–2420.

[129] A. Gomez-Gomez, E. Brito-de la Fuente, C. Gallego, J.Y. Garcia-Perez, J. Benedito, Combined pulsed electric field and high-power ultrasound treatments for microbial inactivation in oil-in-water emulsions, Food Control 130 (2021).

[130] J.T. Guimaraes, E.K. Silva, V.O. Alvarenga, A.L.R. Costa, R.L. Guina, A.S. Sant’Anna, M.Q. Freitas, M.A.A. Meireles, A.G. Cruz, Physicochemical changes and microbial inactivation after high-intensity ultrasound processing of prebiotic whey beverage applying different ultrasonic power levels, Ultrasonics Sonochemistry 44 (2018) 251–260.

[131] P. Hee Kyung, D. Mengyi, F. Hao, Enhancing microbial safety of microgreens: combined ultrasound and warm water treatment as an environmentally-friendly seed sanitation method, Journal of Food Protection 82 (2019) 215.

[132] A. Jalilzadeh, J. Hasarli, S.H. Peighambari, I. Javidpour, The effect of ultrasound treatment on microbial and physicochemical properties of Iranian ultrafiltered feta-type cheese, Journal of Dairy Science 101 (2018) 5809–5820.

[133] M.S. Kim, E.J. Park, Combination of Benzoic Acid and Ultrasound Treatment to Reduce Microbial Contamination on Vegetables, Korean Journal of Food and Cookery, Science 34 (2018) 668–672.

[134] X. Li, H. Xu, P. Liu, Q. Feng, F. Chen, Y. Guo, Utilizing Plackert-Burman design and response surface analysis to optimize ultrasonic cleaning of pesticide residues from rape, Journal of the science of food and agriculture, (2021).

[135] T. Ma, J. Wang, L. Wang, Y. Yang, W. Yang, H. Wang, T. Lan. Q. Zhang, X. Sun, Ultrasound-Combined Sterilization Technology: An Effective Sterilization Technique Ensuring the Microbial Safety of Grape Juice and Significantly Improving Its Quality, Foods 9 (2020).

[136] A. Maryam, R. Anwar, A.U. Malik, M.U. Raheem, A.S. Khan, M. Ul Hasan, Z. Hussain, Z. Siddique, Combined aqueous ozone and ultrasound application inhibits microbial spoilage, reduces pesticide residues and maintains storage quality of strawberry fruits, Journal of Food Measurement and Characterization 15 (2021) 1437–1451.

[137] Z. Yuchen, Z. Ting, X. Dazhui, W. Shaojia, Y. Yingmao, H. Shudong, C. Yanping, The removal of pesticide residues from pakchoi (Brassica rape L. ssp. chinensis) by ultrasonic treatment, Food Control 95 (2019) 176–180.

[138] R. Tavakoli, M. Karami, S. Bahramian, A. Emamifar, Production of low-fat mayonnaise without preservatives: Using the ultrasonic process and investigating of microbial and physicochemical properties of the resultant product, Food Science & Nutrition 9 (2021) 2676–2685.