Power ultrasound for the preservation of postharvest fruits and vegetables

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Abstract: Increasing public demands for improved safety and quality of fruits and vegetables in the fresh market, awaken a growing interest for novel technologies for the preservation of postharvest fruits and vegetables before storage. Ultrasound technology provides one of the methods that with better treating time, enhanced products quality, reduced chemical hazards, low consumption of energy, and is environmentally friendly. This review provides an up-to-date summary of published findings on the application of ultrasound in the preservation of fresh fruits and vegetables. The ultrasound devices commonly utilized, effects of power ultrasound treatment as a factor that affects decay incidence, safety and quality of fresh fruits and vegetables are included. Application challenges and research trends in the future are also analyzed. It is concluded that much progress has been achieved in this field during recent years. These achievements paved the way for the industrial-scale application of ultrasound in the preservation of postharvest fruits and vegetables.

Keywords: power ultrasound, postharvest, fruits and vegetables, decontamination, quality
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1 Introduction

Harvested fruits and vegetables are highly perishable agricultural commodities, and their damaged tissues themselves function as an excellent substrate for the growth of spoilage and pathogenic microorganisms. These microorganisms cause the decay of fresh fruits and vegetables or serve as medium of human disease[1,2]. For a long time, control of microbiological stability of harvested fruits and vegetables largely relies on synthetic chemical fungicides[3]. However, growing concern over the abuse of synthetic fungicides on horticultural products because of their hazards on human health[4] and the emergence of pathogen resistance to fungicides[5] have been putting great limits on this traditional method. Thus a worldwide trend to explore nonchemical alternatives has been occurring. Good results were obtained through some physical methods such as heat treatment, ultraviolet light (UV-C), ionizing-irradiation[6-8] and some biological control methods[9,10]. Ultrasound technology is a rather recent addition to the physical methods used in the decontamination and preservation of postharvest fruits and vegetables[11].

The potential for ultrasound in food industry has been recognized since the 1970s[12]. At high frequencies (100-1000 kHz) and low power (<1 W/cm^2), it can be used as an analytical and diagnostic tool[13]. While

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higher power ultrasound (>1 W/cm^2) at lower frequencies (20-100 kHz), which is referred as "power ultrasound", has the ability to cause cavitation that could be used in food processing, preservation and extraction[14]. In this review, we will focus on the application of power ultrasound in the preservation of postharvest fruits and vegetables. Due to the fact that power ultrasound causes the disruption of microorganism cells, this technology has been applied in food sterilization[15]. However, most applications were involved in the sterilization of liquid foods such as milk, juices, wine and water[14-16]. Until recently, more studies in preservation of fruits and vegetables by power ultrasound were reported[17].

The objective of this review is to provide an up-to-date summary of published findings on the application of ultrasound in the pretreatment of fresh fruits and vegetables. This review summarizes the commonly utilized ultrasound devices, effects of power ultrasound treatment on inactivating and removal of spoilage and pathogenic microorganisms, chemical residues decreasing and dirt cleaning, and maintaining of quality parameters such as texture, color, and nutritional components. Prospect for its commercial application and research trends in the future are also analyzed.

2 Fundamentals of ultrasound technology

2.1 Effect mechanism of ultrasound

Ultrasound is known to cause chemical and physical changes in biological structures (in a liquid medium), owing to the rapid formation and destruction of cavitation bubbles. When ultrasound waves pass through a liquid, a continuous wave type of motion is created. Longitudinal waves are propagated via a series of compression and rarefaction waves, which are induced in the medium particles. If the wave had sufficiently high amplitude, gas bubbles or cavities would be produced in the medium (cavitation process). These cavities contract, expand, and implode with the alternating expansion/compression cycle of the sound waves[18]. Generally, cavitation can be categorized into two types: stable and transient cavitation[19]. Stable cavitation occurs in solutions when the application of low intensities of ultrasound (1-3 W/cm^2) generates a current of microbubbles, which oscillate non-linearly about some equilibrium size for many acoustic cycles. The bubbles induce microstreaming in the surrounding liquid which can induce stress in biomolecules. Transient cavitation occurs during the application of higher intensities of ultrasound (greater than 10 W/cm^2). In this case, the microbubbles begin to oscillate in size but at some point during sonication, they reach a critical size and collapse. At the point of collapse, extreme heat (several thousand Kelvin), high pressure (70-100 MPa) and shear forces are generated and free radicals from water were formed. When these bubbles collapse onto the surface of solid material such as fruits/vegetables, the high pressure and temperature released generate microjets directly towards the solid surface, which are capable of destroying the cells, ejecting the particles from the solid surface, and increase mass transfer to the surface by the disruption of the interfacial boundary layer[20].

2.2 Ultrasonic devices for pretreatment of fruits and vegetables

So far, ultrasound technology used for the pretreatment of fruits and vegetables before storage is still in a small scale experimental phase. On the whole, there are two types of devices utilized in current researches. The major device is an ultrasonic cleaner, of which ultrasonic transducer is bonded to the base of a tank. The fruit/vegetable samples are immersed in the solutions in the tank and exposed to uniform distribution of ultrasonic energy[11,17,21-23]. Besides, an ultrasonic probe system is also applied: the ultrasonic probe is placed some distance (usually several centimeters) from the bottom of a beaver, which contains the mixtures of samples and treatment solution[24,25]. For both devices, frequency and power of ultrasound, temperature of treatment solutions and exposure time can be adjusted according to the experimental requirements. This greatly facilitates the optimization of ultrasonic parameters to get better treatment effect.

3 Use of power ultrasound in preservation of fruits and vegetables

3.1 Decontamination of fruits and vegetables

Various microorganisms (spoilage and pathogen), chemical residues and dirt are the main foreign matters exist in postharvest fruits and vegetables. These matters cause the decay of fresh products and threaten people's health. However, power ultrasound has multifunction in reducing spoilage and pathogenic microorganisms and removing other harmful substances.

3.1.1 Sterilization of spoilage and pathogenic microorganisms

3.1.1.1 Ultrasound used alone

Ultrasonic treatment could significantly reduce the amount of spoilage and pathogenic microorganisms in fruits and vegetables. Actually, microorganisms are directly destroyed or removed by cavitation, which is generally a combination of the following effects[26]: (1) mechanical effects: includes the generation of turbulence, liquid circulation currents and shear stresses; (2) chemical effects: free radicals (H · and OH ·) formed during cavitation in aqueous medium attack the chemical structure of microorganism cell wall and weaken the cell wall to the point of disintegration; (3) physical effects: generation of extreme temperature and pressure locally.

Consequently, there are some studies using power ultrasound alone to treat fresh fruits/ vegetables before storage. These studies arose since the beginning of the 21st century, a variety of fruits and vegetables such as strawberry, peach, persimmon, bean and green asparagus were pretreated with ultrasound[22,27-32] (Table 1). These results demonstrated that ultrasonic treatment significantly reduced the numbers of spoilage microorganisms such as bacteria, yeasts and molds in fresh products, and in turn inhibited decay incidence, extended the storage time of fruits/vegetables.

Table 1 Some examples of microorganisms inactivation of fruits and vegetables by ultrasound

Fruits and vegetables	Microorganism species	Freq[a]/kHz	Power /W	Sample:solution	Tem[b]/℃	Time/min	References
Strawberry	Total bacteria, mold and yeast	40	350	5 kg/20 L	20	10	Cao et al.[22]
Strawberry	Total bacteria, mold and yeast	40	250	5 kg/20 L	9.8	9.8	Cao et al.[27]
Persimmon, peach	-	50	200	40/6 fruits	RT[c]	1-10	Wang et al.[28,29]
Strawberry	Total mesophiles, yeasts and moulds	35	120	160 g/5 L	(15±2)°C	2	Alexandre et al.[30]
Bean	Yeast, mold	-	-	-	RT	20-40	Li et al.[31]
Green asparagus	Bacteria, mold	40	350	250 g	RT	10	Wei[32]

Note: [a] Freq: Frequency; [b] Tem: Temperature; [c] RT: Room temperature.

3.1.1.2 Ultrasound combined with chemicals

Although ultrasonic treatment could reduce the microorganism counts to some extent, however, it used alone may not be adequate for industrial application because of its low sterilization effect[33]. To achieve a satisfying inactivation effect, long treatment time and/or high acoustic energy are required, but this could seriously damage the tissues of fresh commodities and make them more susceptible to the infestation of spoilage microorganisms[11,22,33]. In addition, microorganisms detached from fruits and vegetables will be released into the wash water and thus have the potential to cross-contaminate[11]. In light of these defects, ultrasound is more often combined with other technologies in order to improve sterilization effectiveness.

Among other sterilization methods combined with ultrasound, sanitizers have the most applications. Except killing microorganism cells directly, ultrasound also improves antimicrobial action by weakening the cell wall, which facilitates the penetration of sanitizer agents. In addition to the inactivation action, ultrasonic treatment provides an effective removing action on fruits/vegetables since cavitation bubble collapse near the solid is non-symmetric and produces a powerful jet which will dislodge microorganism cells. The particular advantage of ultrasonic cleaning is that it can reach crevices that are not easily accessible using conventional cleaning methods[34]. Therefore ultrasound waves detach microorganisms from fresh produce into sanitizer solutions, which prompts the exposure of microorganisms that locate in creases and crevices to sanitizer solutions. Consequently, the ultrasound/sanitizers combined treatment shows significant synergistic effect.

In 2002, Seymour et al.[11] studied the microbial decontamination effectiveness of power ultrasound

(25-70 kHz) combined with chlorinated water. Since then, many studies on various fruits and vegetables were reported, involving different sanitizers[23,35]. These sanitizers include synthetic chemicals such as chloric disinfectants (chlorinated water, aqueous ClO_2 and NaClO etc.), H_2O_2, ethanol and natural antimicrobials such as some organic acids (peracetic acid, acetic acid, malic acid, lactic acid and citric acid) were often used (Table 2). As a potential and applicable post-harvest technology, it has attracted wide attention especially in recent three years, during which many studies frequently arose[11,21,25,33,36,37]. These researches demonstrated that the combinational treatment significantly reduced the amount of different species of microorganisms; and ultrasound improved the antimicrobial effectiveness of sanitizers. It was noteworthy that this combinational method was often used to the decontamination of pathogenic bacterias such as *Salmonella Typhimurium, Listeria monocytogenes* and *Escherichia coli* O157:H7 for the sake of its high sterilization effectiveness[11,25,33,35].

On the other hand, salicylic acid (SA) was also combined with power ultrasound to control postharvest diseases of fruits and vegetables. SA is not only an endogenous hormone that plays a critical part in plant growth and development, but a signal molecule that induces the synthesis of plant resistance substance and pathogenesis-related proteins (PRs)[38]. Lots of studies showed that SA could effectively inhibit the decay incidence and prolong the storage life of fresh plant products[39]. When combined with power ultrasound, the combinational treatment also presents a synergetic effect. The reason is that ultrasound could facilitate SA penetration into the tissue cells of fruits and vegetables, a quicker and stronger resistance is induced, and thus decay incidence is significantly inhibited. Yang et al.[17] and Yao et al.[38] investigated the effects of ultrasound and SA either separately or combined on blue mold caused by *Penicillium expansum* in peach fruit and *Yali* pear, respectively. Their results showed that SA alone could reduce blue mold, while the use of ultrasound alone had no effect. However, SA combined with ultrasound was more effective than SA treatment alone. In addition, the combined treatment increased the activities of several defense enzymes such as chitinase, β-1, 3-glucanase, phenylalanine ammonia-lyase (PAL), polyphenol oxidase (PPO) and peroxidase (POD).

Table 2 Some examples of inactivation of microorganisms of fruits and vegetables by ultrasound combined with sanitizers

Satinizers	Fruits and vegetables	Ultrasound conditions	Microorganism species	Log reductions	References
1) NaClO[a] containing 4%-20% available chlorine	Iceberg lettuce	32–40 kHz, 10–15 W/L, 100 g/2 L, 10 min	*Salmonella typhimurium*	2.7	Seymour et al.[11]
2) 40 mg/L ClO_2[b]	Plum fruit	40 kHz, 100W, 1 kg/5 L, 10 min	Total aerobic mesophilic bacteria/ total aerobic psychrotrophic bacteria/ yeasts and moulds	2.0-3.0	Chen et al.[21]
3) 100% acetic acid	Cos lettuce	40 kHz, 20 min	Total bacteria; psychrophile	1-2.5	Ajlouni et al.[23]
4) ASC (10% NaCl solution / 5% citric acid); AEW[c] (80 mg/L); POAA[d] (80 mg/L); Chlorine solution (200 mg/L)	Spinach	21.1 kHz, 200 W/L, 25 g/500 mL, 2 min, RT[g]	*Escherichia coli* O157:H7	0.7-1.1 addition (compared with satinizers alone)	Zhou et al.[25]
5) 99.9% malic acid, 99.0% lactic acid and 99.5% citric acid	Lettuce	40 kHz, 30 W/L, 25 g/500 mL, 5 min	*Escherichia coli* O157:H7/ *Salmonella Typhimurium*/ *Listeria monocytogenes*	2.75/ 3.18 / 2.87	Sagong et al.[33]
6) 20/40 ppm ClO_2 (1 ppm=1 mg/kg)	Apples, Lettuce	170 kHz, 6-10 min, 9 fruits or 90 g/3L	*Salmonella* spp./ *Escherichia coli* O157:H7	3.115-4.253/ 3.115-4.253	Huang et al.[35]
7) NaClO (500 ppm chlorine), H_2O_2[e] (5%) and ethanol (70%)	Fresh *Tuber aestivum, tuber melanosporum* truffles	35 kHz, 10 min, 4℃	*Pseudomonads*/ *Enterobacteriaceae*/lactic acid bacteria and molds	4.0/ 2.0 / 1.5	Rivera et al.[36]
8) 50/200 mg/L SDIC[f]; 5% H_2O_2; 40 mg/L peracetic acid; 10 mg/L ClO_2	Cherry tomato	45 kHz,10 min, 100 g/300 mL, RT	Aerobic mesophiles/Molds and yeasts	0.7-4.4/1.1-3.4	Brilhante et al.[37]
9) 0.1% Tween 20	Lettuce, carrots	40 kHz, 30 W/L, 25 g/500 mL, 5 min	*Bacillus cereus* spores	2.49, 2.22	Sagong et al.[40]

Note: [a] NaClO: Sodium hypochlorite; [b] ClO_2: Chlorine dioxide; [c] AEW: Acidic electrolyzed water; [d] POAA: Peroxyacetic acid; [e] H_2O_2: Hydrogen peroxide; [f] SDIC: Sodium dichloroisocyanurate; [g] RT: Room temperature.

Besides, combined technologies were also used in the reduction of other types of microorganisms. Iceberg lettuce and carrots inoculated with a cocktail of three strains of *Bacillus cereus* spores were treated with combinations of ultrasound and various concentrations of surfactant solutions for five minutes. The most effective treatment for reducing levels of *B. cereus* spores was the combination of ultrasound and 0.1% Tween 20, yielding reductions of 2.49 and 2.22 log CFU/g on lettuce and carrots, respectively, without causing deterioration of quality. These reductions were 1 log greater than those obtained by immersion in 200 ppm (1 ppm=1 mg/kg) chlorine for five minutes. The reduction effect of combined technology was due to the effect of detachment, which could be enhanced by increasing the hydrophile and lipophile balance (HLB) value of surfactants[40].

Some researchers tried to reduce the norovirus, which are currently recognized as the most important human foodborne pathogens using ultrasound combined with other technologies, although these explorations are not very successful. Fraisse et al.[41] reported that a pretreatment step using ultrasound before washing in the presence of disinfectants did not reduce the viral titers on the lettuce more significantly. This demonstrated that the susceptibility of norovirus to ultrasound irradiation was rather low. According to Schultz et al.[42], on fresh raspberries only a 1-log reduction of coliphage, a norovirus surrogate could be achieved after 1 sec of treatment, but at this point damage to the texture of the fresh raspberries was evident.

These results presented above showed that ultrasound/chemicals combined treatments significantly increased spoilage and pathogenic microorganisms sterilization in fresh fruits and vegetables with respect to individual treatments. Due to the synergetic effect, an ideal effect can be achieved under shorter treatment time, lower acoustic energy and lower dosage of chemicals. Therefore, the combinational treatments are low energy-consuming, environment-friendly and much safer.

3.1.2 Reducing chemical residues and cleaning dirt

Ultrasound irradiation has been proved degrading organic chemicals through pyrolytic reactions and the formation of free-radical species caused by cavitation[43]. Therefore, it has been used in the treatment of wastewater for many years. In recent years, ultrasound was also found effective in reducing chemical residues and dirt in postharvest fruits and vegetables[21,44-46]. When ultrasonic waves (100 W ultrasound for 10 min) were combined with aqueous chlorine dioxide (40 mg/L ClO_2 for 10 min) in the pretreating of plum fruits before storage, no ClO_2, ClO_2^- or ClO_3^- residues were detected in the skin or flesh[21].

Some studies focused on the degradation effects of organic chemicals of ultrasound and even optimized the ultrasonic treatment conditions or developed this means in order to improve its effectiveness. Gong et al.[44] combined ozone water treatment with ultrasound (power 360 W, temperature 35℃, for 20 min) to degrade the pesticides in commercially available apples and obtained an improved removal rate compared with single ultrasound and single ozone treatment. According to the study of Yue et al.[45], under the optimum technological conditions (power 609.16 W, temperature 15.45℃ for 70.46 min), the removal rate for organochlorine pesticide residues in apples reached 64.32%. Besides, ultrasound (40 kHz, 180 W)/detergent treatment was also used to clean the dirt embeds on mushroom root. Under the optimum condition (detergent 0.67%, sample:water = 1:100, temperature 21.5-25.0℃ for 20 min), the cleaning efficiency can be increased 55.5% and more edible parts of the rare mushroom was obtained than that without sonication[46]. These results showed that ultrasound significantly reduced chemical residues and dirt in fruits and vegetables, therefore improved their edible safety.

3.2 Maintaining quality parameters of fruits and vegetables

Texture, color and nutrients constitute the critical quality attributes of fruits and vegetables. Since fruits and vegetables picked from the whole plants, they went to ripening, senescence and death gradually, followed by the deterioration of texture and color, and the decrease of nutrients[21,22]. Current studies showed that ultrasonic pretreatment could inhibit the physiological activities and retard the quality decline of fresh products during storage, presenting as a potential technology in the preservation of fresh fruits and vegetables.

3.2.1 Texture

Texture not only connects with the edible quality of products, but also is an indicator of storage property and effect. Firmness is a visual trait that directly represents the texture of fruits and vegetables. Due to the physiological activities such as respiration and transpiration, firmness of fresh products decreases gradually during storage, largely influencing quality and facilitating pathogen infection.

Many studies demonstrated that pretreatment using ultrasound could delay the softening of fruits and vegetables[21,22,28-30,32,47] (Table 3). One possible reason is that ultrasonic treatment inhibits the activities of enzymes that are largely responsible for fruit softening such as pectin methylesterase (PME) and polygalacturonase (PG)[22]. However, no direct evidences have been reported to prove this hypothesis. On the other hand, the rate of enzymatic breakdown of cell wall components have been demonstrated depending on the energy produced through respiration[48]. Thus the decrease of respiration might be one of the reasons that the enzymatic activities were reduced. In addition, water loss resulted from the transpiration and ethylene production of fruits and vegetables also influences the firmness of fruits and vegetables[49], but studies into the effect of ultrasound on these physiological activities have not been reported yet. Further researches into these questions at molecular and biochemical levels will help us understand the mechanisms about how ultrasound maintains the firmness.

Table 3 Salient effects of ultrasound treatment on firmness and nutritional components of fruits and vegetables

Fruits and vegetables	Ultrasound conditions	Effects on firmness	Effects on nutritional and flavor components	References
Plum fruit	40 kHz, 100 W, 1 kg/5 L, 10 min	Inhibit the respiration rate and maintain fruit firmness	Ultrasonic method was effective in preserving contents of total flavonoids, ascorbic acid, reducing sugars, and titratable acids.	Chen et al.[21]
Strawberry	40 kHz, 350 W, 5 kg/20 L, 10 min, 20℃	The firmness in 40 kHz ultrasound-treated fruit was 17.5% higher than that in control fruit on the 8th day.	TSS and TA levels in 40 kHz ultrasound-treated fruit were 7.7% and 22.2% higher, respectively, than that in control fruit after 8 days of cold storage; Significantly higher level of vitamin C in 40 and 59 kHz ultrasound-treated fruit was observed compared to control.	Cao et al.[22]
Persimmon, peach	50 kHz, 200 W, 1-10 min, RT[a]	Inhibit the decline of fruit firmness during storage.	Decreases of TSS and TA were inhibited after ultrasonic treatment; their contents were significantly higher than control at the end of storage.	Wang et al.[28,29]
Strawberry	35 kHz, 120 W, 160 g/5 L, 2 min, (15±2)℃	After 6 days at room temperature, sonicated samples lost 21% of firmness, while 67% of losses were observed for water-washed strawberries.	After 4 days during storage, VC was rarely detected in controlled group, while averaging 16% of the initial content can be detected in ozonated and ultrasonicated strawberries.	Alexandre et al.[30]
Green asparagus	40 kHz, 350 W, 250 g, 10 min, RT	The firmness in 60 and 100 kHz ultrasound-treated fruits were 1.82 N and 2.09 N higher than that in control fruits, respectively, on the 15th day.	After 20 d storage, total flavonoids and total phenols were significantly higher than control; after 15 d storage, VC of products treated with 20, 40, 60 kHz ultrasound were 23.9%, 40.4% and 23.9% higher than control, respectively.	Wei[32]
Fragrant pear	50 kHz, 200 W, 3 min, RT	Inhibit the respiration rate and maintain fruit firmness	–	Zhao et al.[47]

Note: [a] RT: room temperature.

3.2.2 Color

Color is an important sensory quality of fresh fruits and vegetables and depends on the pigments they contain. Chlorophyll, carotenoid and anthocyanin are the major pigments. After harvesting, these pigments began to degrade, so the color deteriorated gradually, which significantly decreased the acceptance of fresh products. Fortunately, recent studies showed that pretreatment with ultrasound could retard the degradation of pigments[30,32]. Alexandre et al.[30] discovered the inhibition of anthocyanin declining in strawberries treated with ultrasound. Wei[32] also reported that ultrasound played a positive role in maintaining the color of green asparagus, but if the power was too high, ultrasonic treatment would make a reverse effect. Since the degradation of pigments were processes comprised of a series of enzymatic reactions, it can be inferred that the enzymatic degradation of pigments was inhibited to some extent by ultrasound irradiation.

The effects of ultrasound irradiation on enzyme activities could be confirmed by several studies on enzymatic browning, which greatly influenced the color of postharvest fruits. Chen et al.[50] treated the *Guiwei* litchi with ultrasound at power 120 W for 10 min in water and then stored at room temperature (28℃). They found that application of ultrasound generally reduced the degradation of litchi anthocyanins and inhibited the activities of PPO and POD at the early storage stage and, thus, significantly delayed pericarp browning of litchi fruit. Similarly, the investigation of Jang et al.[51] revealed that simultaneous treatment with ultrasound and ascorbic acid had synergistic inhibitory effects on several enzymes related to enzymatic browning, including monophenolase, diphenolase, and POD.

3.2.3 Nutritional components

It is well known that fruits and vegetables are the main dietary source of vitamin C (VC), and also are rich in many other nutritional components such as polyphenol, flavonoid, saccharides and organic acids. Thus they are functional in keeping people healthy and have specific flavors. In recent years, many researchers explored the maintenance of these nutritional components through ultrasonic pretreatment before storage[21,22,28-30,32] (Table 3). In these researches, contents of VC, total flavonoids, total phenols, total soluble solids (TSS), reducing sugars and titratable acids (TA) were compared between several types of fruits/vegetables with and without ultrasonic treatment. Results showed that these components were maintained at higher levels in ultrasound treated fresh products. Cao et al.[22] attributed these results to the fact that ultrasound inhibited decay incidence and microbial population of strawberries. However, respiration plays a major role in the loss of these components, since they are the main substrates of respiration in post-harvest fruits and vegetables. Coincidently, the respiratory intensity can also be retarded after ultrasonic treatment[22,47], it can be concluded that the inhibition of respiration might be the major mechanism for the maintenance of nutrients.

3.2.4 Mechanism for vegetal responses

As discussed above, the post-harvest fruits/vegetables underwent ripening, senescence and death gradually, followed by the deterioration of texture and color, and the decrease of nutrients[21,22]. Recent discoveries have ascertained that fruit senescence is greatly related to reactive oxygen species (ROS) and incidental oxidative damage of mitochondrial protein[52]. Interestingly, there is a scavenging system of ROS in plants, including superoxide dismutase (SOD), catalase (CAT), POD, ascorbate peroxidase (APX) and glutathione peroxidase (GPX) etc. It was reported that the activities of these enzymes were elevated after ultrasonic treatment[47,53]. Zhao et al.[47] detected higher POD and SOD activities of fragrant pears with ultrasound and MA packaging than individual treatments and control group during storage. In addition, in the study of Li et al.[53], harvested peaches were treated with ultrasound (50 kHz, 200 W), $CaCl_2$ (3%) immersion or their combination for 3 min. Both ultrasound and $CaCl_2$ treatments increased the activities of SOD and CAT in various extents, decreased the activity of POD, the production rate of O_2^-, or the contents of H_2O_2 at different periods of storage. Besides, the combinational treatment presented a synergetic effect as ultrasound facilitated the penetration of $CaCl_2$. However, so far no study has explored the deep mechanism for the changes of ROS scavenging enzymes after ultrasonic treatment.

Many researchers have studied the effect of ultrasound on biomolecules such as enzymes. In enzymatic reaction systems in vitro, ultrasound plays binary functions[54]: on the one hand, it facilitates the contact between enzymes and substrates, thus improves the efficiency of enzymatic reactions; on the other hand, the mechanic, physical and chemical effects of cavitation could denature the proteins and inactivate the enzymes. However, the responses to ultrasonic waves might be much more complicated when it comes to the multicellular tissues of fruits and vegetables. Till now, few studies have reported the effects of ultrasound on muticellular plant tissues. Further study on the physiological responses to ultrasonic treatment at biochemical and molecular level is urgently needed.

4 Challenges and trends

Although the potential of ultrasound on postharvest fruits and vegetables preservation have been well understood, there remains a long way to go before this technology can be considered for commercialization. Generally, there are still several problems that hinder the wide application of ultrasound. The first challenge is the non-standardized reporting of methodology and control parameters. Standardized reporting in terms of energy intensity, probe types, and sample quantities is necessary for exploring the selection of ultrasound parameters to improve treatment effect and would facilitate techno-economic assessment prior to industrial application[55]. Secondly, from the economic point of view, the cost of energy requirement would be higher and the equipment more costly compared with other physical methods such as heat treatment, UV-C technology etc.[56,57]. Besides, the lethal effects of ultrasound irradiation on microorganisms are not sufficient for it to be used alone. For this reason, it is rather combined with other hurdles for better effectiveness. However, probably because of the difficulties in feasibility, combinations between ultrasound and other sterilization technologies, such as heat and/or pressure, UV-C light, pulsed electric fields etc., which although have been widely combined with ultrasound in sterilization of liquid foods[14,16], are only beginning to be studied in the sterilization of fresh products. These deterrents determined that the future research in the coming years for the purpose of wide application of ultrasound in postharvest fruits and vegetables will be: (1) exploring the selection of ultrasound processing variables through standardized description of methodology and control parameters; (2) improving the equipment properties and researching into industrial scale-up[58,59]; (3) combing ultrasound with other preservation technologies. These studies would improve treatment effects, reduce the cost of equipment and energy consumption, and ultimately provide applicable guide for industrial scale using.

5 Conclusions

Reduction of microorganisms, chemical residues and dirt, improving the organoleptic and nutritional properties show that the ultrasound based technologies may have a high potential in the preservation of postharvest fruits and vegetables. Even if these technologies are not likely to completely replace traditional processing methods, they can certainly complement or be integrated with the existing ones. However, the explorations for the technology are just at its preliminary stage. Further researches into the biochemical and molecular mechanisms of vegetal response to ultrasound irradiation, optimization of processing efficiency, improving the equipment properties, combinations with existed technologies (e.g. heat and/or pressure, UV-C light, pulsed electric fields etc.), and researching into industrial scale-up would be necessary before industrial scale application. The progress of this technology and its commercialization will further result in a low energy-consumption, environment friendly tool to provide safe, nutritious fruits and vegetables for consumers at an affordable cost.

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