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Review

The state-of-the-art research of the application of ultrasound to winemaking: A critical review

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ABSTRACT

As a promising non-thermal physical technology, ultrasound has attracted extensive attention in recent years, and has been applied to many food processing operation units, such as involving filtration, freezing, thawing, sterilization, cutting, extraction, aging, etc. It is also widely used in the processing of meat products, fruits and vegetables, and dairy products. With regard to its application in winemaking, most of the studies available in the literature are focused on the impact of ultrasound on a certain characteristic of wine, lacking of systematic sorting of these literatures. This review systematically summarizes and explores the current achievements and problems of the application of ultrasound to the different stages of winemaking, including extraction, fermentation, aging and sterilization. Summarizing the advantages and disadvantages of ultrasound application in winemaking and its development in future development.

1. Introduction

Wine refers to the fermented wine with certain alcohol content, which is made from fresh grapes or grape juice through partial or total fermentation. Generally, the main factors affecting winemaking include grape variety and quality, winemaking methods and fermentation strains. In recent years, with the development of science and technology, more and more novel technologies have begun to be integrated into the winemaking process in order to improve its efficiency and the quality of the resulting wine [1].

Ultrasound is a physical technology that has been used to accelerate the extraction, freezing, filtering, dehydration and sterilization processes in the field of food processing [2–5], which can enhance the performance of these processes and improve the quality characteristics (color, aroma and aroma substances, texture, nutritional value, security) and extend shelf life of the food products[6]. The ultrasound mechanism is attributed to the acoustic cavitation and its induced sonochemical effect. The acoustic cavitation consists of the formation, growth and violent collapse of small bubbles or voids in liquids. This violent bubble collapse is responsible for extreme localized pressure (up to 1000 atm) and temperature (up to 5000 °C), resulting in the formation of free radicals.

In the early stage, the reports about ultrasound application in wine were mainly focused on accelerating the ageing of Baijiu (distilled spirit), while the research in this field was not valued for a long time, due to the phenomenon of wine regeneration during storage after ultrasound irradiation [7–10]. In recent years, several applications of ultrasound in the production of wines and juices at laboratory scale have been reported. To be specific, ultrasound has been used to enhance heat transfer, to detect microbial contamination, to reduce membrane fouling in beverage clarification, to inactivate microorganisms, to clean equipment, to monitor processes, and to improve extraction and to accelerate reactions within beverages [11].

As a result, more and more attention has been paid to the application of ultrasound in winemaking with the in-depth understanding of ultrasonics sonochemistry by researchers. However, due to the differences of ultrasound equipment and grape varieties, the obtained results differ greatly among different research groups. Furthermore, most of these studies are mainly focused on the application of ultrasound to a certain part of the winemaking process, and there is a lack of systematic review of the literature related to its application to the whole winemaking process.

In this paper, a comprehensive review was conducted on references of ultrasound application in the four main stages of winemaking, i.e.

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extraction, fermentation, aging and sterilization, so as to provide some important basic data to wine producers for its potential industrial application.

2. Ultrasound and its application

Ultrasonic wave is a part of sound wave, inaudible to human ears, and which frequency is higher than 20 kHz [12]. When the sound wave passes through a medium, the ultrasound cavitation releases a large amount of energy, and causes localized, instantaneous high temperatures and high pressures, resulting in the microflow phenomenon and accelerating the mass transfer. Its basic working principle is attributed to the reflection and scattering of sound waves, similar to light waves [13]. Generally, ultrasound can be divided into low-intensity and high-intensity ultrasound according to its power and frequency, as shown in Fig. 1.

According to the working modes of ultrasound, it can be divided into dynamic ultrasonic equipment such as continuous and circulating type, and static ultrasonic equipment such as ultrasound baths and ultrasound probes [14], the static ultrasonic equipment being more commonly used in the laboratory. Ultrasound bath is a widely used and easy to be operated instrument, which is usually consisted of a container filled with a liquid (generally a water bath), a timer knob, a heater and at least one ultrasonic transducer, as shown in Fig. 2(a). The instrument usually uses a beaker, flask or test tube is used as sample container, which is semi-immersed in the liquid and fixed in a specific position to obtain the maximum cavitation effect [2]. An ultrasound probe usually consists of a generator, a line connected to the control panel, a transducer, and a sample container that can be fixed on the desired position, and sometimes also includes a stirring and a temperature control system, as shown in Fig. 2(b). Water bath type and probe type ultrasound have their advantages and disadvantages, as shown in Table 1.

3. Application of ultrasound in winemaking process

3.1. The winemaking process

Although the wine making process may vary in detail, the basic process is similar (Fig. 3). Firstly, the harvested grapes are crushed to break the skins and release the sugary colorless juice [1]. Then fermentation is carried out, which is divided into two stages: main fermentation and post fermentation. The main microorganisms affecting the wine fermentation process include *Saccharomyces* cerevisiae, non-*Saccharomyces* cerevisiae, lactic acid bacteria [16]. In the process of fermentation, to let stand grape juice along with grape skins is beneficial to the growth and reproduction of yeast, and a large amount of skin residue can be observed on the liquid surface, because the skin residue cannot release heat in time, the temperature is more conducive to fermentation at this time. During the main fermentation (alcoholic fermentation), as the nutrients in grape skins and seeds are transferred to the fermentation liquid, the flavor and bright color of the wine are increased, but the fermentation time should not be too long, otherwise it will lead to excessive tannin concentration, which will make the wine bitter and affect its taste [17]. Then the malolactic fermentation takes place, which reduces the acidity and roughness of raw wine, makes it soft and round, and also improves the sensory quality and biological stability of wine =. When the acidity of wine is relatively high, that is, when malic acid – lactic acid fermentation is most needed, this fermentation is more difficult to trigger. Under this condition, mild chemical acid reduction will increase the pH value to 3.2, which is conducive to the triggering of malic acid-lactic acid fermentation. As a result, fermentation gradually stops and aroma gradually increases. Then clarification and aging can be carried out (Fig. 4.).

Aging can be divided into maturation (oxidative aging) and bottle aging (reductive aging) [3]. The newly brewed wine contains many monomeric tannins. Aging in oak barrels (maturation) and bottles can reduce the bitterness of tannins and make the wine more full-bodied. Finally, the sterilization process of wine is mainly to kill harmful microorganisms in wine and prolong its shelf life.

3.2. Ultrasound as an extraction technique

In the process of winemaking, it is often involved in the migration of substances in grapes, skins and stems, and the enrichment and detection of substances in fermentation liquid. Conventional methods have problems such as time-consuming, require a large amount of solvents and have low efficiency [18]. Ultrasound extraction and separation technology, characterized by high efficiency and convenience, has been reported in many applications in winemaking [19,20]. During ultrasound-assisted extraction, the material produces microbubbles due to the action of ultrasonic cavitation, and their rupture produces several physical and thermal effects, which will eventually accelerate the transfer of compounds from grape skins and seeds to must and improve the extraction efficiency [21,22]. The application of ultrasonic waves in the grape juice making process can significantly promote the improvement of juice yield and color. The first possible mechanism is that the ultrasonic cavitation effect leads to the breaking of grape tissue cell wall, which is conducive to the full exudation of juice and pigments, thus improving juice yield and color. Second, ultrasonic mechanical vibration effect accelerates the transfer process of compounds, so that polyphenols can be quickly transferred from grape skins and seeds to juice. Ultrasound frequency, power density, amplitude and temperature are the most important parameters that affect the ultrasonic effect. Cavitation at low frequency produces larger bubbles, and with the increase of local temperatures and pressures, bubbles burst more violently. With the increase of frequency, more bubbles burst per time unit [21,23]. Ultrasound can accelerate the migration of phenols and other substances from grape skins and seeds to must during grape crushing, and the mass transfer follows the mass transfer kinetics model of Fick's second law [24,25].In terms of ultrasound application in grape juice making process, Palma et al. [26] studied the ultrasound-assisted extraction of organic acids in wine and wine by-products by using ultrasound probes

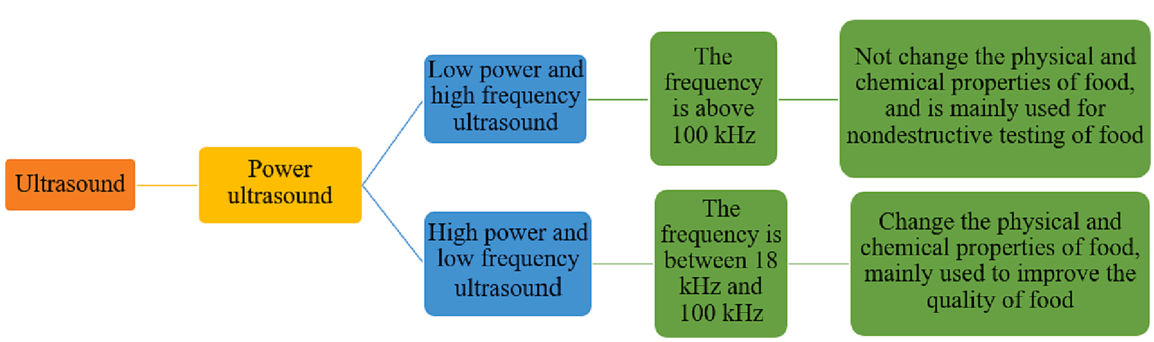

Fig. 1. Classification of ultrasound by the size of ultrasonic vibration radiation.

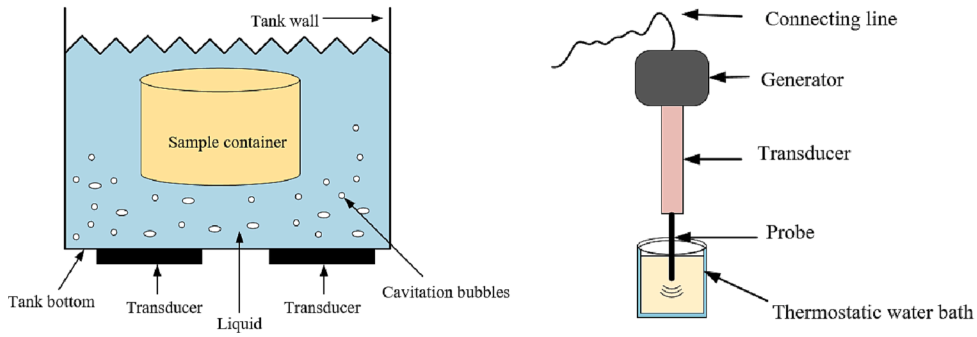

Fig. 2. Ultrasound equipment: (a) ultrasound bath mode (b) ultrasound probe mode [15].

Table 1
Comparison between ultrasound bath and ultrasound probe.

	Ultrasound bath	Ultrasound probe
Popularity	Easier to popularize	Difficult to popularize
Price	Lower	Expensive
Operability	Easy to operate	Difficult to control temperature
Intensity obtained	Lower	Higher
Contamination on reaction liquid	No	From corrosion of the probe surface
Processing scale	Relatively large	Relatively small

at 200 W, 24 kHz, amplitudes from 30 to 90%, and treatment times from 120 to 1500 s. The results showed that ultrasound-assisted extraction improved the contents of tartaric acid and malic acid in wine and wine by-products. Dujmic et al. [27] studied the extraction of polyphenols in wine by-products under the conditions of 400 W, 22 mm probe diameter, 90% amplitude and 25 min extraction time, and the results showed that the extraction rate was significantly improved. Plaza et al. [28] found that when ultrasound was applied to grape vinification process, it not only promoted the extraction of phenolic compounds from grapes, but also shortened the impregnation time, and obtained wine with good color characteristics. In the same line, Romero-Díez et al. [29] under the ultrasound conditions of amplitude of 55% and temperature of 25 ℃, obtained that ultrasound treatment improved the extraction rate of anthocyanin from wine lees and therefore shortened the extraction time. Ferraretto et al. [30] also studied the influence of ultrasound on grapes during in the vinification process. These authors found an improvement in the extraction of polyphenolic compounds from grapes due to the disruption of the cell wall caused by pressure alternance and cavitation provoked by ultrasound, resulting in a reduction in the length of classic maceration. Besides, the ultrasound-assisted yeast lysis released different fractions to the wine. Dalagnol et al. [31] studied the effects of ultrasound, mechanical agitation and nine industrial enzyme preparations on Cabernet Sauvignon grape juice production. Compared with mechanical agitation, ultrasound-assisted extraction improved the extraction rate of anthocyanins, and the combination of ultrasound, mechanical agitation and enzymatic hydrolysis showed a synergistic effect on the extraction of grape juice. Darra et al. and Carrera et al. [32,33] all assayed the ultrasound-assisted extraction of phenolic compounds from grapes and found that this method shortened extraction time and increased the content of phenolic compounds. Bautista-Ortín et al. [34] studied the influence of ultrasound treatment on the maceration stage, and determined the wine chromatic characteristics and the anthocyanins and tannin concentrations. The authors found that ultrasound treatment could significantly shorten the maceration time and increase the content of tannins and volatile compounds in the resulting red wine. Martínez-Pérez et al. [35] made a comparison between wines obtained by sonicated vinification from Monastrell red grapes (29.0 °Brix ripening level) and two wines obtained by classical vinification from Monastrell red grapes harvested with two different ripening levels (25.4 °Brix and 29.0 °Brix), and found that the total phenolic compounds and tannin contents of the two wines from the less mature grapes were similar, but the alcohol content of the wine produced by applying ultrasound was 15% lower. The authors concluded that the ultrasound-assisted-extraction of phenolic compounds from grapes, even when grape phenolic maturity is not complete, allows the production of

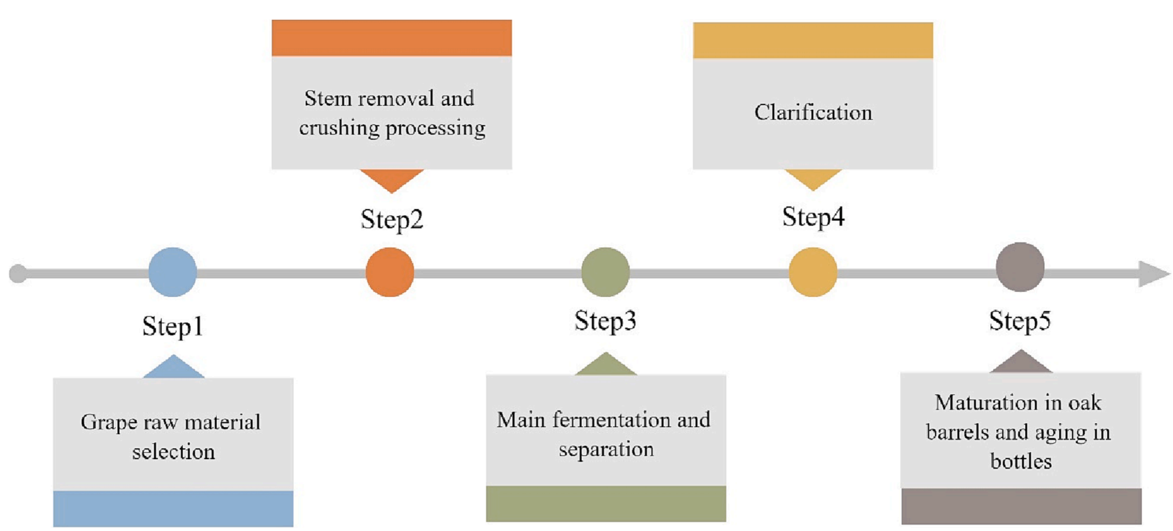

Fig. 3. Procedure of grape wine making [1].

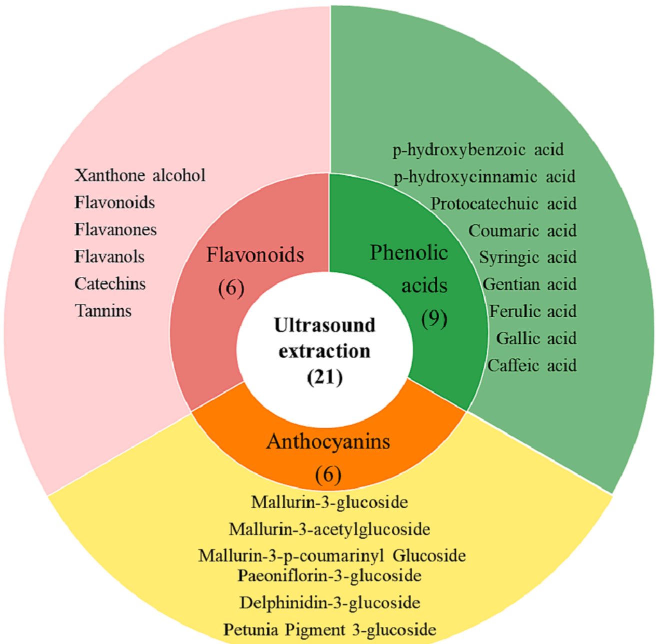

Fig. 4. Ultrasound assisted extraction of nutrients during winemaking.

quality wines with a reduced alcohol content (Fig. 5).

As can be seen from the above analysis (Table 2), ultrasound-assisted extraction has the advantages of high maceration efficiency and short extraction time. However, there are also the following disadvantages worth overcoming and solving: first, when the maceration container is large, the sound wave is not easy to radiate to every place, resulting in poor extraction effect; Second, ultrasound maceration energy consumption is relatively large; Third, the use of ultrasound probes is prone to cause pollution due to probe erosion and thus spoilage of wine by metal elements.

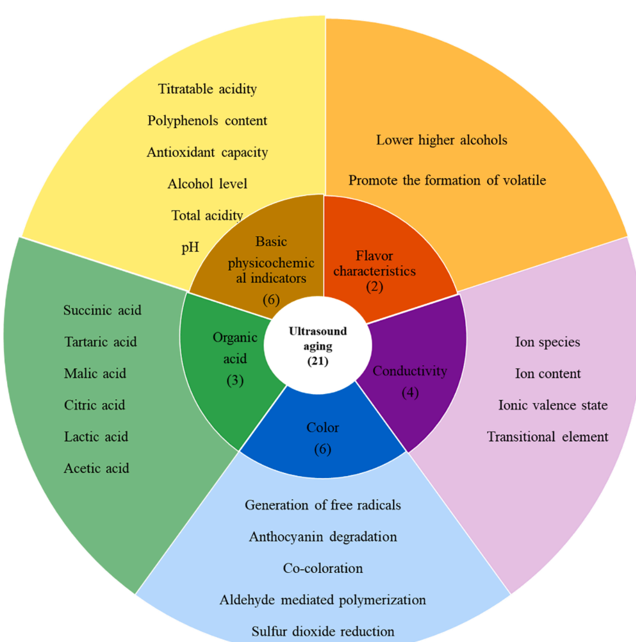

Fig. 5. Application of ultrasound in wine aging.

3.3. *Research progress in application of ultrasound to wine fermentation*

Fermentation is one of the key processes in winemaking, which can be divided into alcoholic fermentation and malolactic acid fermentation. During the alcoholic fermentation stage, yeasts, mainly *Saccharomyces cerevisiae*, transform sugars into ethanol, carbon dioxide and other substances. In the malolactic fermentation stage, alcohols can undergo esterification, redox and other reactions, improving wine taste and flavor. Over the fermentation process, nutrients in grape skins and seeds are transferred to the fermentation liquid, and the skin residue can float on the surface of grape mash due to the action of carbon dioxide to form a “skin cap”, thus affecting the fermentation performance. Stirring and other operations are often needed to destroy the residue cap and promote the full contact between the skin residue and the fermentation liquid. If ultrasound is applied, the turbulence provoked by cavitation can make grape skins and stalks oscillate rapidly in the fermentation liquid, and then accelerate the mass transfer process. The application of ultrasound in the process of microbial fermentation can instantly cause micro injury on the cell surface and local rupture of the cell wall, so as to change the permeability of the cell membrane and make the intracellular substances be released or the extracellular substances enter the cell [43].

In addition, the natural fermentation cycle of wine is generally long, easy to contaminate by miscellaneous bacteria. The equipment occupies a large area and the fermentation process requires relatively high labor intensity, which reduces the production efficiency of enterprises and increases the production cost [44,45]. In order to overcome the above problems, researchers began to try to use ultrasound in wine fermentation, and achieved certain results. When ultrasound is used in wine fermentation, on the one hand, it can improve the permeability and selectivity of yeast cell membrane, stimulate the secretion and metabolism of enzymes and improve the fermentation rate; on the other hand, it can kill miscellaneous bacteria and improve the quality of wine [46]. Changes in cell membranes are mainly attributed to mechanical oscillations and free radicals (e.g. H·and·OH) generated by the sonochemical and physical effects induced by ultrasound [47]. Japanese scholars have found that in the process of wine fermentation, the increase of carbon dioxide concentration hinders yeast growth and delay the generation of ethanol, making the fermentation cycle longer. Besides, carbon dioxide inhibits the formation of ester compounds, thus affecting the aroma characteristics of wine [48–50]. However, ultrasonic radiation can reduce the water-soluble carbon dioxide in the fermentation tank, promote the formation of aroma substances such as ethanol and esters, shorten the fermentation time and enhance the aroma of wine [51]. According to the different frequency of ultrasound, the role of ultrasound in the process of wine fermentation can be divided into two categories: one is to monitor the changes of substances in the fermentation process by high-frequency ultrasound, while the other is to use low-frequency ultrasound to extract compounds from grape skins and stalks and activate yeast metabolism or kill miscellaneous bacteria.

3.3.1. *Application of high-frequency ultrasound in wine fermentation*

The traditional monitoring method of the fermentation process is to take samples regularly to determine the changes of key fermentation parameters such as microbial growth, pH value, acidity, turbidity and chemical composition. This method is time-consuming and complex to operate. However, the use of high-frequency ultrasound can provide reliable information to characterize the real-time fermentation process of wine [52]. High-frequency ultrasound is usually used as a nondestructive analysis technique in wine fermentation to ensure product quality and monitor the fermentation process. High-frequency ultrasound using low power level, which is not enough to cause acoustic cavitation, generates sound waves through the material that produce zero or minimum physical and chemical changes. The ultrasound exposure time, power or frequency can be adjusted to obtain the desired sound energy into the wine and control cavitation, and so the technology

Table 2
Application of ultrasound-assisted maceration in wine and its by-products.

Sample	Ultrasound condition	Extracted compounds	Main result	Reference
Red wine lees	Power 400 W, the probe diameter 22 mm, the amplitude 90%, 25 min	Polyphenols	Increased maceration rate of polyphenols	[27]
Red wine	Frequency 28 kHz, power 2500 W	Anthocyanins, tannins	The content of tannin increased	[34]
Grape must and wine	Frequency 24 kHz, 37 kHz, power 20–75 W, 200 W	Polyphenols	Improvement of polyphenols maceration rate	[36]
Grape juice	Frequency 20 kHz 10 min, pulse treatment of 5 s on and 5 s off	Anthocyanins	The maceration rate of anthocyanins increased	[37]
Red wine lees	Frequency 20 kHz, power 200 W	Polysaccharide	Accelerated release of polysaccharides from wine lees	[38]
Red wine lees and model wine	Frequency 25 kHz, power 300 W	Polyphenols and tartrate esters	Improvement of polyphenols and tartrate esters extraction rate	[24]
Grape must and wine	Frequency 48 kHz for 10 min	Fruit acids and aromatic compounds	Extraction time shortened	[39]
Bio-products of wine making	Frequency 24 kHz, power 200 W	Tartaric acid and malic acid	The content of phenolic compounds increased significantly	[40]
Red wine	Frequency 35 kHz, power 2000 W, 15 min	Polyphenols	Ultrasound maceration did not favor polyphenols extraction from grape skins and the obtained wines were poor in anthocyanins and tannins	[41]
Grape pomace	Frequency 20 kHz, power 130 W, probe diameter 13 mm	Phenolic compounds	Shorten extraction time of phenolic compounds	[42]

can be used for wine fermentation monitoring analysis and quality control [52]. Measurement systems based on acoustics are non-invasive, hygienic, accurate, fast, low-cost and automatic [53,54]. Ultrasonic waves have been used in the fermentation process to monitor the change of substances and solution concentration [55,56]. Table 3 summarizes the available literatures on monitoring wine fermentation process by high-frequency ultrasound.

High-frequency ultrasound can be used to monitor the fermentation process of wine in real-time. Novoa-Díaz et al. [53] and Amer et al. [57] used ultrasound to monitor malolactic fermentation. The authors correlated the ultrasonic velocity to the conversion of malic acid into lactic acid and CO_2 by lactic acid bacteria. As malic acid is converted into lactic acid during fermentation, ultrasound propagation speed is accelerated, so that the ultrasound velocity could be used to predict the end of the malolactic fermentation process. Resa et al. [58] reported that the concentration of alcohol and sugar in the fermentation process could be predicted through the ultrasound speed of the fermenter.

3.3.2. Application progress of low frequency ultrasound in wine fermentation

Low-frequency ultrasound, also known as high-power ultrasound, uses high power to produce cavitation, and as a consequence, chemical reactions [48]. In the food industry, it can be used for degassing, homogenization and extraction [61,62]. In food fermentation, low-frequency ultrasound can activate enzymes and regulate microbial metabolism, eliminate foam, and improve product quality. At the same time, it can also play the role of antiseptic and sterilization.

Table 3
Application of high-frequency ultrasound in wine fermentation.

Sample	Ultrasound mode	Ultrasound frequency	Ultrasound effect	Reference
Wine	Pulsed ultrasound	1 MHz	Monitor the lactic acid fermentation in wine	[53]
Model wine	Pulsed ultrasound	2 MHz	Monitor the density and ultrasonic velocity during fermentation of a mixture of water, ethanol and sucrose	[58]
Model wine	Pulsed ultrasound	2 MHz	Monitor the concentration of malic and lactic acid during the malolactic fermentation in mixtures	[59]
Model wine	Pulsed ultrasound	2 MHz	Determin the concentration of yeast and maltose in the model solution	[60]

Wine producers cope with the problem of spoilage caused by contamination of miscellaneous bacteria. The traditional solution is the addition of sulfur dioxide and other chemicals [3,63–65], but these compounds have safety concerns. Therefore, the search for new substitutive materials or new techniques in this field has become a hot topic, and low-frequency ultrasound processing technology is one of them. The use of ultrasound in the fermentation process, because of its good bactericidal effect, can effectively reduce the amount of SO_2 that should be added in the fermentation liquid, while improving the quality of wine color, taste and so on. The mechanisms of its action are changes in the existing form of SO_2 in fermentation liquid by ultrasound cavitation, which increases the amount of combined sulfur dioxide, and produces sulfur-containing free radicals that undergo oxidative polymerization or degradation reaction with carbonyl compounds, phenolic compounds, etc. in wine, making the change of wine color.

Low-frequency ultrasound can activate the metabolism of *S. cerevisiae* and other yeasts during wine fermentation, and also increase yeast lysis thus releasing substances (mannoproteins, polysaccharides, etc.) to wine, which can speed up the wine fermentation rate and shorten the fermentation time (Table 4). Dai et al. [66] showed that the biomass growth of *S. cerevisiae* increased by 127.03%, compared with the control group, under optimal ultrasound conditions (ultrasound frequency 28 kHz, power 140 W/L and treatment time 1 h). Besides, ultrasound treatment enhanced the membrane permeability of *S. cerevisiae*, activated the wine yeasts, and accelerated the migration of nucleic acids and nutrients such as fructose-1,6-diphosphate from yeast cells to the fermentation medium. The fermentation time was shortened 36 h compared with the control group. Xiong [67] carried out alcohol fermentation tests with *S. cerevisiae* by using a small fermenter, and the results showed that low-frequency ultrasound could promote the proliferation and growth of *S. cerevisiae* cells and improve the fermentation efficiency of *S. cerevisiae*, and Logistic model could well predict ultrasound-assisted alcohol fermentation of *S. cerevisiae*. Hong et al. [68] reported that ultrasound treatment (ultrasound frequency 40 kHz, ultrasound power 50 W, temperature 30 ℃) can stimulate yeasts to produce by-products such as higher alcohols and probiotics, and meanwhile reduce the CO_2 produced in the metabolic process, thus promoting cell proliferation and biological metabolism, increasing enzyme production, accelerating biological metabolism and releasing compounds from the inner cell to the fermentation medium.Matsuura et al. [69] studied the influence of ultrasound treatment on the fermentation processes of wine, beer and sake, and found that ultrasound can reduce the level of dissolved carbon dioxide concentration in the fermentation process, increase the content of esters in wine, promote the formation of iso-amyl acetate, make the wine taste more mellow and shorten the fermentation

Table 4
Applications of low-frequency ultrasound to wine fermentation.

Sample	Ultrasound condition	Aim	Result	Reference
Red wine	Frequency 26 kHz, power 118 W, 20 min	Control the microbial spoilage during wine fermentation	Reduction of the cell survival rate of spoilage microorganisms in wine and improvement of the flavor and aroma characteristics	[65]
S. cerevisiae	Frequency 28 kHz, power 140 W/L, 1 h	Assess the effects of low-intensity ultrasound on *S. cerevisiae* at different growth stages were studied	Enhancement of the cell membrane permeability of *S. cerevisiae*, yeast activation, acceleration of the migration of nutrients from cells to fermentation medium, and shortening of the fermentation time	[66]
White wine	Frequency 40 kHz, 20 min	Assess the effects of different fermentation processes on microbial stability and quality of low-alcohol white wine	Ultrasound combined with SO_2 treatment greatly reduced the content of *S. cerevisiae* after fermentation, and improved the biological stability of wine	[71]
Red wine	Temperatures of 30℃ and 40℃, frequency 24 kHz, power 400 W, amplitude 100 µm, 60 s	Evaluate the effects of ultrasound on yeasts and lactic acid bacteria in wine	Yeast and lactic acid bacteria inhibition, reduction of the amount of SO_2 and preservatives	[72]

time. Qu et al. [44] found that ultrasound could affect the enzyme activity and metabolic pathway of yeasts, making the aroma and taste of wine significantly different. Simancas et al. [70] studied the influence of low-frequency ultrasound on fermentation products in wine, and the results showed that ultrasound had a positive impact, improving the content of volatile compounds related to sensory attributes and making the wine aroma stronger (Table 5).

3.3.3. Current hindrances of the application of ultrasound in wine fermentation

The information illustrated in the previous sections which demonstrates the application of ultrasound technology in wine fermentation provides certain benefits to the winemaking process and, therefore, to wines. High-frequency ultrasound can dynamically monitor the changes during fermentation process in real-time, and low-frequency ultrasound can promote yeast growth and the production of ethanol, thus shortening the fermentation time, and enhance the aroma of wine. However, for low-frequency ultrasound, when the ultrasound power is too high and the treatment time too long, excessive cavitation can damage *S. cerevisiae* cells, thus delaying fermentation. At the same time, the degradation of polyphenols in the fermentation medium affects the flavor and quality of wine. Therefore, for the use of low-frequency ultrasonic waves in the wine fermentation process, the choice of ultrasound intensity, yeast concentration and processing time is of major importance to avoid these problems. In addition, in order to reduce the potential contamination from metal elements caused by ultrasonic cavitation erosion of stainless steel containers, it is recommended that ultrasound waves do not directly contact the wine, therefore, the use of ultrasound probes should be avoided.

Table 5
The advantages and disadvantages of ultrasonic applications in red wine processing.

Red wine processing	Advantages	Disadvantages
Ultrasound-assisted maceration	High maceration efficiency Shorten extraction time	Large maceration container will lead to poor extraction effect Ultrasound-assisted maceration energy consumption is relatively large
Fermentation	High-frequency ultrasound can dynamically monitor the changes during fermentation process in real-time Low-frequency ultrasound can promote yeast growth and the production of ethanol, shorten the fermentation time, and enhance the aroma of wine	Long treatment time will delay fermentation Ultrasound probe mode will cause wine pollution
Aging	Accelerate the maturation of wine Shorten the aging time Improve the taste and overall quality of wine	None
Sterilization	Shorten the sterilization time, reduce nutrient loss Improve product stability and extend shelf life	Only applicable to liquids or objects soaked in liquids The handling capacity should not be too large

4. Advances in the application of ultrasound in wine aging

4.1. Aging of wine

Wines can be matured or aged and these terms refer to different stages of development of the wine. Notwithstanding, these two terms are generally used rather confusingly [73]. Thus, it is widely accepted for most of winemakers and consumers that wine maturation in oak barrels is wine aging. As a result, it can be said that wine aging is composed of two stages: maturation (oxidative aging) and bottle aging (reductive aging) [3,74], although maturation is not regarded as an aging stage by wine experts.

Maturation takes place after fermentation, during which wine may undergo malolactic fermentation, be submitted to clarification processes or stored in oak barrels [3]. In general, maturation in the winery prepares wines for their useful lifetime, the time in which a wine is good to drink. The maturation process is intended to stabilize the wine and enable it to be drunk pleasantly and enjoyably on its commercial release [74].

Bottle aging (reductive aging) is usually related to the time wine spends in bottles in almost absence of oxygen and in this type of development wines can proceed from youth, through to maturity and, eventually, to a fading away of any worthwhile flavor [74]. The amount of dissolved oxygen in wines stored in bottles depends on the type of the closure and the materials of the bottle. Wines are usually stored in glass bottles with airtight caps to minimize oxygen exposure [75]. Bottle aging allows the development of more complex wine flavors over around 20 years or more.

Then comes a point in time at which the wine is deemed to be drinking at its best. It said that the wine has reached its “peak”, which can last for another 20, or 50 or even 100 years [73]. At this stage, the aroma components in the wine gradually increase and accumulate, and the taste is round, the wine body is harmonious, the color is bright, and the quality is the best. Finally, there is a declining period, where the aromas are still intense at the beginning of this phase and then gradually fade [76].

Not all grapes lead to wines with potential to age. In some instances, it is because the grape cannot does not provide acidity or tannins enough to protect the wine but in the majority of cases it is because the general belief that wines from such grapes do not develop pleasing flavors with time [73]. Tannins, for example, react with the proteins present in saliva to produce a mouth-drying effect so that wines with high tannin level are regarded as astringent. During aging, tannins eventually reduce as polymerization in the bottle results in higher molecular-weight tannin complexes, which are unstable in wine and precipitate, forming the sediment in the bottle. Besides, the wine loses color over time as these complexes also contain anthocyanins [73].

A wine worthy to be aged must have a number of preservatives and be made in such a way as to be able to develop new flavors over time. White wines must have a low pH or high levels of residual sugars to help to protect them against all forms of microbial spoilage. Red wines have tannins as their main preservative, pH also being important [73]. In both cases, sulfur dioxide is commonly added to wine to manage spoilage organisms and for its good antioxidant properties, although the addition of SO_2 to wine can give a reductive aroma to wine [3]. The traditional method of wine maturation or oxidative aging is to store the wine in oak barrels for a period of time, where the esters, phenols and aldehydes in the oak are transferred to the wine to increase the complexity of the flavor. The special structure of oak makes it impermeable and breathable, which allows a certain amount of oxygen to enter the wine during aging in oak barrels, resulting in a moderate redox reaction, accelerating the maturation process and making the wine round and harmonious; at the same time, the tannins and pigments in the wine are combined into large molecules and precipitated, as aforementioned, changing the color of the wine from bright red to brick red.

However, the traditional method of aging wine in oak barrels has some drawbacks: first, it is time-consuming, and the maturation process in oak barrels usually takes several months to years; second, oak barrels are expensive, occupy a large area, and have to be replaced over time; third, the aging process is susceptible to microbial contamination and corruption [3]. In order to overcome the problems of the traditional maturation-aging process of wine, researchers have been exploring new alternative technologies.

4.2. Principles of ultrasound-assisted wine aging

New aging technologies have been reported for physical aging such as ultrasound treatment, pulsed electric field treatment, radiation treatment, and ultra-high pressure treatment [1,3,77–81]. In comparison, wine aging using pulsed electric fields and ultra-high pressure, which is currently more researched, more effective, and more promising for industrial applications. Notwithstanding, ultrasound, as a non-thermal physical processing method, has also received a lot of attention from researchers and is considered a promising new technology for accelerating wine aging [3,75,79,82].

In China, the research on ultrasound treatment of ripening wines started in the 1970s, and the main target of this research was white wines, but the technology did not receive much attention due to the problems of "rejuvenation" and the difficulty of controlling the conditions (Here a reference is needed). In recent years, there has been a "warming" phenomenon in the domestic research on the application of ultrasonic wave to the aging of wine [83].

The countries where ultrasound aging research was conducted earlier were the former Soviet Union and the United States. In the 1950s, several translations of Soviet books on the application of ultrasound in the food industry mentioned ultrasound aging of wine. In the 1960s, Singleton and Draper carried out research at the University of California related to the use of ultrasound to accelerate the maturation of red wine, but it was limited to the research conditions at that time, and the changes in the physicochemical properties of wine after ultrasound treatment were not significant and irregular. Besides, the resulting wine had a burnt taste, so the technology did not receive much attention at that time [74]. In Japan, research was also carried out in the last century on the effect of ultrasound on the formation mechanism of water clusters between ethanol and water molecules in wine and the quality of wine [84–86]. Since the 21st century (especially in the last 15 years), in China, several research institutes have carried out research on ultrasound-assisted wine aging and made a series of progress; as for the rest of the world, the main countries with more research on ultrasound-assisted wine aging are Italy, Spain and Argentina.

Ultrasound-assisted wine aging mainly occurs through the ultrasonic rupture of tiny bubbles in the liquid caused by the cavitation effect, which causes the local instantaneous temperature and pressure rise, generating free radicals and triggering a series of complex chemical reactions among the wine compounds, potentially accelerating chemical reactions related to wine aging. First, ultrasound can promote association and enhance the affinity between polar molecules, such as ethanol and water, and can even form larger, firmer polar molecules. Certain esters, acids and other wine components may also be involved in these bonds and form part of these larger molecules, so as to improve the softness and coordination of the wine. Second, ultrasound can reduce the activation energy of certain reactions. As a result, ultrasound can accelerate esterification, condensation, redox and degradation reactions within wine, and improve its alcohol-ester aroma and flavor. Third, the mechanical effect of ultrasound also can promote the volatilization of low-boiling-point components in wine and accelerate the extraction of flavor substances from oak barrels and yeasts. The above effects are regarded to accelerate the maturation of wine, shorten the aging time, and improve the taste and overall quality of wine [87].

4.2.1. Research progress in the application of ultrasound to wine aging

There are two main ways to apply ultrasound to age wines. One is to treat the wine directly with ultrasound to accelerate the chemical reactions associated with aging. The other is to use ultrasound in combination with oak barrels, oak chips, yeasts and fermentation residues to accelerate the release of flavor substances to wine and promote acoustic-chemical reactions, which ultimately allows the wine to mature and age rapidly and improve its quality [78,81,82,88]. Based on the effects and mechanisms of ultrasound on relevant compounds in wine, current research has focused on the following aspects:

(1) The effect of ultrasonic aging treatment on the basic physicochemical indicators of wine

Total acidity, titratable acidity, alcohol level, polyphenols content, color, conductivity, and antioxidant capacity of wine are all physicochemical properties of interest to wine producers, so whether these properties of wine are affected by ultrasound during rapid aging is also an important indicator for judging the feasibility of this technology.

Wine contains large amounts of phenolic compounds that are related to its antioxidant capacity. Hu et al. [89] demonstrated the strong antioxidant capacity of wine using electron paramagnetic resonance spectroscopy, and that it was related to its total phenols content. Fernandez- Pachón et al. [90] showed that the antioxidant capacity of red wine is related to phenolic and flavonoid substances. Acidity and pH are very important for the stability of wine, the main volatile acid in wine being acetic acid, which at high concentrations produces vinegary "off flavors" [3]. Studies have demonstrated that ultrasound of wine cannot significantly affect the pH and titratable acidity of white and red wines [91,92]. Shen et al. [91] determined the influence of ultrasound treatment on the phenolic content and free radical scavenging rate in red wine, and compared the ultrasound-treated wines with the group of wines without ultrasound treatment. The phenolic content, DPPH and hydroxyl radical scavenging rate were significantly increased, that is, ultrasound significantly improved the antioxidant properties of red wine, while it has no significant effect on wine quality parameters, such as alcohol content, total acid and titratable acid. Zhang et al. [77]

investigated the effects of ultrasound treatment under the condition of power of 100 W and frequency of 20 kHz on the color characteristics and changes in major phenolic compounds during wine aging, and the results showed that ultrasound treatment significantly improved the color of wine and accelerated the aging process. Shu et al. [92] reported that when intermittent sonication time was short and ultrasound power was low, ultrasound treatment enhanced anthocyanin content in wines, which promoted color presentation, accelerated the aging process, and made wines more harmonious. Celotti et al. [93] showed that the content of anthocyanins and phenolic compounds in wine increased continuously when increasing the amplitude and the sonication time. Li [94] used ultrasound probe to treat wine and showed that when the ultrasound power, the treatment time and the number of treatments were increased, and the chromaticity values of the wine increased, especially those that had a co-color effect on the wines. Zhang et al. [95] showed that ultrasound can improve the sensory characteristics of wine by modulating the interactions between phenolic compounds and proteins from yeast autolysis through a model wine. Liu et al. and García Martín et al. [96,97] showed that ultrasound can enhance yeast autolysis and increase the polysaccharide content in wine by increasing the rate and extent of yeast cell destruction without adversely affecting the sensory quality of wine. In addition, it could also promote the improvement of wine flavor to some extent. Tao et al. [88] studied the treatment of a model wine by ultrasound combined with oak chips. The results showed that the compounds released by oak chips enhanced the aroma of wine. Besides, ultrasound treatment increased the mass transfer and migration of phenols from oak chips to the model wine, and the content of total phenols in the model wine increased significantly after 150 min of ultrasound treatment. Juan et al. [98] showed a reduction in astringency, an increase in polysaccharide content and aromatic substances, an improvement in the harmonization of the wine and shortening of the aging time when red wine was treated with ultrasound in combination with oak chips and lees. Delgado-González et al. [99] found that the color intensity and phenolic compounds concentration of wine distillate showed an increasing trend when acoustic energy density was 40 W/L in their study on the effect of oak chips combined with ultrasound on wine aging. Yan et al. [100] showed that ultrasound has a significant effect on the electrical conductivity of wine, and the mechanism may be that ultrasound can affect the concentration, ionic valence and ionic strength of metal ions in wine. To be specific, ultrasound can oxidize Fe^{2+} to Fe^{3+}.

(2) Mechanisms and progress of ultrasonic treatment on wine color

The changes on wine color induced by ultrasound may be due to several factors, such as the generation of free radicals and their chain reactions (oxidative polymerization, condensation, etc.), co-color effects and reduction of sulfur dioxide in wine.

It was found that 1-hydroxyethyl free radical was produced in wine under ultrasound treatment, and this radical is a key radical in the maturation process of wine [101], which is the basis for the occurrence of related reactions during wine maturation; the mechanisms of its production may be due to the transient high temperatures and pressures generated locally by ultrasonic cavitation that cause the cleavage of water molecules in wine to produce hydroxyl radicals, which subsequently react with ethanol to form 1-hydroxyethyl radicals [4,102]. The 1- hydroxyethyl radical is then transformed into acetaldehyde, which acts as a bridge chain to mediate the polymerization of anthocyanins and flavan-3-ols to produce compounds responsible for color, thereby improving the color of the wine [83]. The color change caused by ultrasonic treatment of wine is also related to its auxochromatic effect: Li [94] showed that 20 kHz, 180 W ultrasound treatment for 20 min can enhance the auxochromatic effect by changing the structure of auxochromes (caffeic acid, etc.), which in turn accelerates the color change and the maturation of wine, the obtaining wines remaining stable after one month of storage without reversible changes. Xue et al. [103] reported the effect of 100 W power ultrasound treatment for 0 min, 14 min and 28 min on the co-color effect of caffeic acid and catechin in wine and model wine, and the results showed that ultrasound can not only affect the co-color effect of co-colorants, but also have significant differences on the co-color effect of different substances. Fu et al. [104] showed that 25 kHz, 500 W ultrasound treatment for 20 min could significantly promote the formation of pigment-like substances in model wines, thus improving the color quality of wines. In addition, Chen et al. [105] reported the effect and mechanism of sulfur-containing compounds on wine color in red wine and model wine under ultrasound (25 kHz, 500 W, and 20 min).

(3) Research progress on the influence of ultrasonic aging on wine flavor characteristics

There are many flavor-related substances in wine, some of them are volatile. Ultrasound treatment of wine affects its flavor to some extent. On the one hand, ultrasonic cavitation causes changes in flavor-related compounds in the wine, on the other hand, ultrasound can cause the loss of low-molecular-weight volatile compounds in the wine (degassing effect) [106]. The research of Sánchez-Córdoba et al. [107] showed that ultrasound treatment during pre-fermentative maceration of red wine did not modify the sensory profile of the wines while when applied over aging with oak chips, ultrasound extracted large amounts of volatile compounds from oak chips that provided red fruits, aromatic intensity and wood attributes, which was regarded by the authors as a positive trend at sensory level. Lukić et al. [108] studied the effect of ultrasound treatment on color and aroma compounds and found that ultrasound treatment significantly reduced the content of higher alcohols; however, the most suitable ultrasound conditions should be established to avoid excessive oxidation and degradation of phenolic compounds and compounds responsible for wine aromas. The authors also systematically studied the effects of ultrasonic aging on volatile flavor compounds and higher alcohols in wine. The results showed that ultrasound could significantly reduce the content of higher alcohols (40.44% reduction), and there were significant differences in the effects of different types of ultrasonic instruments (numerical control ultrasound cleaning machine, multi-frequency ultrasonic cleaner system and variable-amplitude ultrasound-rod cell disrupter). At the same time, ultrasound could also increase the types and content of volatile flavor compounds, indicating that ultrasound treatment can improve the taste and flavor characteristics of wine to some extent [109–111]. Chemat et al. [112] studied the relationship between ultrasound treatment and phenolic compounds degradation in wine, and the results showed that ultrasound treatment could prevent oxidative degradation of aromatic compounds. Lukić et al. [108] found that ultrasound frequency had the highest effect on the physicochemical parameters of red wine aging, followed by ultrasound temperature and amplitude. The lower the ultrasound frequency, the shorter the aging time, and the lower the amplitude and temperature, the more favorable the phenolic compounds, color, and aroma components in wine; the higher temperatures of water-bath ultrasound leads to the degradation of volatile compounds, while the larger probe diameter and the higher amplitude of ultrasound probe have less effect on phenols and volatile components. Cui et al. [113] showed that ultrasound treatment accelerated the cleavage of wine yeast more than microwave treatment, resulting in an increase in the content of aromatic compounds and esters and a decrease in the content of higher alcohols, and make the wine body more harmonious and color more stable.

4.2.2. Prospects of ultrasound wine aging technology

In summary, the available studies have shown that ultrasound, combined or not with oak chips, can indeed affect in a positive way the quality of wine to a certain extent and accelerate the aging of wine. The aim is to achieve wines that have the flavor and quality characteristics of wines traditionally aged but in a much shorter time.

However, the problems in the current studies include: First, most of the current research focus on the macroscopic description of the changes in physicochemical and sensory parameters of wine by ultrasound treatment, while research on the mechanism of ultrasound aging is rarely involved. Second, the ultrasound equipment used, the parameter conditions assayed and the results obtained by the various research groups are very different, which cannot provide a reference for later research. Third, the available results in the literature cannot provide definitive information on the feasibility of the industrial scale-up of the aging of wine by ultrasound. In particular, the changes and mechanism of substances closely related to bitterness, astringency, browning and color in wine after ultrasonic treatment are still unclear. Changes in these compounds and attributes during the maturation and aging in barrels of wine are relatively clear, which is convenient to assess whether wines treated with ultrasound resembles to those naturally matured and aged.

Therefor it is suggested to conduct the first research by constructing a model wine system composed of the main compounds found in wine (or at least those related to aging) to eliminate the interferences from non-target compounds. In this way, the effect mechanism of ultrasound on the quality parameters and sensory characteristics of wine can be studied more deeply and systematically, providing theoretical basis for the commercial application of ultrasound aging.

4.2.3. Research progress of ultrasound for wine sterilization

This step of winemaking takes place after the completion of alcoholic fermentation and other fermentation processes. In order to stop the fermentation process in time and prevent the spoilage and pollution by other bacteria, sterilization or the addition of chemical preservatives (such as sulfur dioxide) are usually carried out. Ultrasound is regarded as a new type of physical sterilization process, and its mechanisms of action is the transient, local high pressures and high temperatures generated by ultrasonic cavitation bubbles when they rupture, which are sufficient to disrupt the cell wall structure of microorganisms and cause bacterial death [62]. Studies have shown that ultrasound has good sterilizing effects, which is helpful to avoid the adverse effects caused by traditional thermal and chemical sterilization processes, reduce processing time and nutritional loss, and maintain the original flavor of food [114–116]. In general, there are many factors that affect the performance of ultrasound sterilization, such as the size and morphology of microorganisms, ultrasound power, amplitude and frequency, and processing time and temperature [117]. Cells with larger surface area are more susceptible to ultrasound cavitation [118], and Gram-positive bacteria and spherical cells have stronger resistance to ultrasound than Gram-negative bacteria and rod-shaped cells. Budding spores and some heat-resistant microorganisms also have stronger resistance [119]. Joyce et al. [120] showed that at low frequency range (between 20 kHz and 38 kHz), the killing rate of *Bacillus* increased significantly with the increase of treatment time and ultrasound intensity. Pagán et al. [121] found that combined ultrasound and microwave treatments were more effective for inactivating *Listeria monocytogenes*. Gracin et al. [72] found that continuous high-power ultrasound treatment was effective in inhibiting *Brettanomyces* yeasts and lactic acid bacteria in wine up to 89.1–99.7% and 71.8–99.3%, respectively. Bevilacqua et al. [122,123] reported that ultrasound treatment at 20 kHz, 130 W, 20–60% amplitude and 2–6 s pulses for 2–6 min was effective in reducing the number of *Brettanomyces* yeasts and some harmful microorganisms, and extending the shelf life.

In the wine sterilization process, ultrasound can also be combined with other methods such as heat treatment and sulfur dioxide addition in order to shorten the sterilization time, reduce the loss of nutrient, and achieve better sterilization results. Cui et al. [71] carried out research on the treatment of white wine by ultrasound combined with sulfur dioxide. The results showed that ultrasound under the most suitable conditions (40 Hz ultrasound for 20 min and 40 mg/L SO_2) had higher total lethal rate of *S. cerevisiae*, and improved the biostability, the flavor and quality of wine. Finally, Lv et al. [124] combined high pressure electrostatic field, ultrasound and pasteurization, respectively, with traditional sulfite treatment for wine, and the results showed that ultrasound combined with sulfur dioxide treatment was the most effective, with characteristic aroma and flavor, and remained clear and transparent after 12 months of storage, improving product stability and extending shelf life.

5. Future prospects for research and industrial application

From the information provided in the previous sections, it can be concluded that ultrasound can be reasonably applied in the various steps of winemaking to accelerate mass transfer, activate yeasts to speed up fermentation metabolism, shorten aging time, reduce SO_2 consumption, improve wine quality characteristics, extend shelf life, and other beneficial effects. However, the following problems in the application of basic research and industrial application of the technology still remains to be overcome.

First, most of the current researches on ultrasonic treatment of wine are conducted under laboratory-scale conditions, and the results obtained are not consistent. Therefore, basic laboratory research should continue to be strengthened to clarify the basic requirements needed for the use of ultrasound in each step. In terms of ultrasound power, it is recommended the use of power density to describe the ultrasound conditions to unify the ultrasonic power.

Second, ultrasound used is mostly static ultrasound, which leads to relatively large energy consumption and strong corrosion to the container, which is not suitable for industrial mass production. Therefore, it is recommended the development of suitable ultrasound equipment for large-scale application.

Thirdly, the mechanisms of ultrasound working in the different steps of winemaking is not completely clear, which to a certain extent limits its commercial application. It is suggested to carry out interdisciplinary research in different fields to lay the theoretical basis for large-scale applications.

Fourth, it is recommended that ultrasound be combined with other methods. To be specific, in order to substitute the maturation in oak barrels, ultrasound could be combined with the addition of oak chips to obtain the tannins and volatile compounds from wood.

CRediT authorship contribution statement

Qing-An Zhang: providing funding, supervision, revising and editing the manuscript. **Hongrong Zheng:** writing the original draft, drawing the figures and editing manuscript. **Junyan Lin:** drawing the figures and writing the original draft. **Guangmin Nie:** writing the original draft. **Xuehui Fan:** revising and editing the manuscript. **Juan Francisco García-Martín:** revising and editing the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] M.L. Clodoveo, T. Dipalmo, C.G. Rizzello, F. Corbo, P. Crupi, Emerging technology to develop novel red winemaking practices: an overview, Innov. Food Sci. Emerg. Technol. 38 (2016) 41–56.
[2] X.-Z. Fu, T. Belwal, G. Cravotto, Z. Luo, Sono-physical and sono-chemical effects of ultrasound: primary applications in extraction and freezing operations and influence on food components, Ultrason. Sonochem. 60 (2019), 104726.
[3] J.F. García-Martín, D.-W. Sun, Ultrasound and electric fields as novel techniques for assisting the wine ageing process: The state-of-the-art research, Trends Food Sci. Technol. 33 (1) (2013) 40–53.
[4] Y. Shen, Effect of Ultrasound on Physicochemical Indexes of Red Wine and its Mechanism, Shaanxi Normal University, Xi'an, 2015 in Chinese.
[5] Y. Tao, D. Li, W.-S. Chai, P.-L. Show, X. Yang, S. Manickam, G. Xie, Y. Han, Comparison between airborne ultrasound and contact ultrasound to intensify air drying of blackberry: Heat and mass transfer simulation, energy consumption and quality evaluation, Ultrason. Sonochem. 72 (2021), 105410.
[6] W. Gong, X. Zhao, S. Manickam, X. Liu, D. Li, Y. Han, H. Kiani, C. Feng, Y. Tao, Impact of cell wall adsorption behaviours on phenolic stability under air drying of blackberry with and without contact ultrasound assistance, Food Hydrocoll, 137, (2023), 108312.
[7] Jiang Su Yang He distillery, Study on artificial aging of new wine. Food Ferment. Ind. 2, (1976), 22-33. (in Chinese).
[8] D. Ding, A brief talk on ultrasonic acceleration of wine ripening, Wine Making 2 (1985) 22–23, in Chinese.
[9] Z.-H. Pan, Discussion on artificially accelerating wine aging, China Brew. 04, (1986), 6-13+46. (in Chinese).
[10] F.-W. Liu, Using integrated electronic technology can make new wine mature, Wine Making 1 (1988) 25–27, in Chinese.
[11] J.F. García Martín, Applications of Ultrasound in the Beverage Industry, Nova Publishers, New York, 2016.
[12] C.Q. Howard, C.H. Hansen, A.C. Zander, A review of current airborne ultrasound exposure limits, J. Occupat. Health Safety of AUS. NZL 21 (3) (2005) 253–257.
[13] A.R. Jambrak, Application of high power ultrasound and microwave in food processing: extraction, J. Food Process. Technol. 12 (03) (2012) 3–12.
[14] X.-W. Guo, F.-Y. Gao, New Technology of Ultrasonic Extraction and Separation, Chemical Industry Press, Beijing, 2018, pp. 19–28, in Chinese.
[15] N. Bhargava, R.S. Mor, K. Kumar, V.S. Sharanagat, Advances in application of ultrasound in food processing: a review, Ultrason. Sonochem. 70 (2020), 105293.
[16] W.-X. Wang, Z.-N.-N. Gulimire, Z.-C. Du, X.-H. Liu, P.-C. Lu, Y. Wu, The impact of microorganisms on wine quality from a new perspective, Chinese Foreign Grape Wine 06 (2020) 78–83, in Chinese.
[17] M. Pinelo, A. Arnous, A.S. Meyer, Upgrading of grape skins: Significance of plant cell-wall structural components and extraction techniques for phenol release, Trends Food Sci. Technol. 17 (11) (2006) 579–590.
[18] S.R. Shirsath, S.H. Sonawane, P.R. Gogate, Intensification of extraction of natural products using ultrasonic irradiations-A review of current status, Chem. Eng. Process. Process Intensif. 49 (3) (2010) 10–23.
[19] A.S. Moreira, M.C.E. Alexandre, M. Pintado, A.J. Saraiva, Effect of emergent non-thermal extraction technologies on bioactive individual compounds profile from different plant materials, Food Res. Int. 115 (2019) 177–190.
[20] A.-J. Hu, J. Zheng, Food Ultrasonic Technology, Chemical Industry Press, Beijing, 2013, pp. 74–75, in Chinese.
[21] C.-T. Wen, J.-X. Zhang, H.-H. Zhang, Advances in ultrasound assisted extraction of bioactive compounds from cash crops-A review, Ultrason. Sonochem. 48 (2018) 538–549.
[22] D. Panda, S. Manickam, Cavitation technology-the future of greener extraction method: a review on the extraction of natural products and process intensification mechanism and perspectives, Appl. Sci. 9 (4) (2019) 1–21.
[23] F. Chemat, N. Rombaut, A. Meullemiestre, M. Turk, S. Perino, A.S. Fabiano-Tixier, M. Abert-Vian, Review of green food processing techniques. Preservation, transformation, and extraction, Innov. Food Sci. Emerg. Technol. (2017) 357–377.
[24] Y. Tao, Z. Zhang, D.-W. Sun, Kinetic modeling of ultrasound-assisted extraction of phenolic compounds from grape marc: Influence of acoustic energy density and temperature, Ultrason. Sonochem. 21 (4) (2014) 1461–1469.
[25] J.-Q. Liao, Study on Modeling and Frequency Optimization of Ultrasonic Extraction Process of Natural Product and its Application, Jiangnan University, 2017 in Chinese.
[26] M. Palma, C.G. Barroso, Ultrasound-assisted extraction and determination of tartaric and malic acids from grapes and winemaking by-products, Anal. Chim. Acta. 458 (1) (2002) 119–130.
[27] F. Dujmic, K.K. Gani, D. Uri, S. Karlovi, T. Bosiljkov, D. Jeek, R. Vidrih, J. Hribar, E. Zlati, T. Prusina, Non-thermal ultrasonic extraction of polyphenolic compounds from red wine lees, Foods 9 (4) (2020) 472–491.
[28] E. Gómez-Plaza, A. Osete-Alcaraz, R. Jurado, J.A. Iniesta, A.B. Bautista-Ortín, The application of high power ultrasounds for improving the phenolic extraction and color from grape-derived products, Acta Hortic. 1274 (2020) 1–8.
[29] R. Romero-Díez, M. Matos, L. Rodrigues, M.R. Bronze, S. Rodríguez-Rojo, M. J. Cocero, A.A. Matias, Microwave and ultrasound pre-treatments to enhance anthocyanins extraction from different wine lees, Food Chem. 272 (2018) 258–266.
[30] P. Ferraretto, V. Cacciola, I. Batlló, E. Celotti, Ultrasounds application in winemaking: Grape maceration and yeast lysis, Ital. J. Food Sci. 25 (2) (2013) 160–168.
[31] L.M.G. Dalagnol, L.D. Magro, V.C.C. Silveira, E. Rodrigues, V. Manfroi, R. C. Rodrigues, Combination of ultrasound, enzymes and mechanical stirring: A new method to improve *Vitis vinifera* Cabernet Sauvignon must yield, quality and bioactive compounds, Food Bioprod. Process. 105 (2017) 197–204.
[32] N.E. Darra, N. Grimi, R.G. Maroun, N. Louka, E. Vorobiev, Pulsed electric field, ultrasound, and thermal pretreatments for better phenolic extraction during red fermentation, Eur. Food Res. Technol. 236 (1) (2013) 47–56.
[33] C. Carrera, A. Ruiz-Rodríguez, M. Palma, C.G. Barroso, Ultrasound assisted extraction of phenolic compounds from grapes, Anal. Chim. Acta. 732 (2012) 100–104.
[34] A.B. Bautista-Ortín, M.D. Jiménez-Martínez, R. Jurado, J.A. Iniesta, S. Terrades, A. Andrés, E. Gómez-Plaza, Application of high-power ultrasounds during red wine vinification, Int. J. Food Sci. Technol. 52 (6) (2017) 1314–1323.
[35] M. Martínez-Pérez, A. Bautista-Ortín, P. Pérez-Porras, R. Jurado, E. Gómez-Plaza, A new approach to the reduction of alcohol content in red wines: the use of high-power ultrasounds, Foods 9 (6) (2020) 726–738.
[36] A. Coletta, A. Trani, M. Faccia, R. Punzi, T. Dipalmo, P. Crupi, D. Antonacci, G. Gambacorta, Influence of viticultural practices and winemaking technologies on phenolic composition and sensory characteristics of Negroamaro red wines, Int. J. Food Sci. Technol. 48 (11) (2013) 2215–2227.
[37] B.K. Tiwari, A. Patras, N. Brunton, P.J. Cullen, C.P. O'donnell, Effect of ultrasound processing on anthocyanins and color of red grape juice, Ultrason. Sonochem., 17(3), (2010), 598-604.
[38] V. Cacciola, I.F. Batllò, P. Ferraretto, S. Vincenzi, E. Celotti, Study of the ultrasound effects on yeast lees lysis in winemaking, Eur. Food Res. Technol. 236 (2) (2013) 311–317.
[39] C. Cocito, G. Gaetano, C. Delfini, Rapid extraction of aroma compounds in must and wine by means of ultrasound, Food Chem. 52 (3) (1995) 311–320.
[40] C. Droso, K. Kyriakopoulou, A. Bimpilas, D. Tsimogiannis, M. Krokida, A comparative study on different extraction techniques to recover red grape pomace polyphenols from vinification byproducts, Ind. Crops Prod. 75 (2015) 141–149.
[41] T. Tudose-Sandu-Ville, V.V. Cotea, C. Colibaba, B. Nechita, M. Niculaua, M. Codreanu, Phenolic compounds in Merlot wines obtained through different technologies in Iai Vineyard, Romania, Cercetari Agronomice MDA 45 (4) (2012) 89–98.
[42] A.M. Goula, K. Thymiatis, K. Kaderides, Valorization of grape pomace: Drying behavior and ultrasound extraction of phenolics, Food Bioprod. Process. 100 (2016) 132–144.
[43] H.-G. Qu, L.-H. Yang, Y.-W. Sun, P. Zhang, J. Miu, Effects of ultrasonic wave on fermented capability of saccharomyces serevisiae and wine quality, Food Sci. 03 (2007) 216–219.
[44] X.-L. Gao, E.-M. Liu, J.-K. Zhang, L.-X. Yang, L. Liao, Accelerating aroma formation of raw soy sauce using low intensity sonication, Food Chem. 329 (2020), 127118.
[45] A.D. Villiers, P. Alberts, A. Tredoux, H.H. Nieuwoudt, Analytical techniques for wine analysis: An African perspective; a review, Anal. Chim. Acta. 730 (2012) 2–23.
[46] A. Gholamhosseinpour, S.M.B. Hashemi, Ultrasound pretreatment of fermented milk containing probiotic Lactobacillus plantarum AF1: Carbohydrate metabolism and antioxidant activity, J. Food Process Eng. 42 (1) (2019) 1–9.
[47] H. Yu, Y. Liu, L. Li, Y.-H. Guo, Y.F. Xie, Y.-L. Cheng, W.-R. Yao, Ultrasound-involved emerging strategies for controlling foodborne microbial biofilms, Trends Food Sci. Technol. 96 (2020) 91–101.
[48] A. Nose, M. Myojin, M. Hojo, T. Ueda, T. Okuda, Proton nuclear magnetic resonance and Raman spectroscopic studies of Japanese sake, an alcoholic beverage, J. Biosci. Bioeng. 99 (5) (2005) 493–501.
[49] Y. Matsuura, Effects of ultrasonic wave irradiation in ethanol fermentation, Beverage. 10 (1998) 40–42.
[50] F. Ge, Application of ultrasonic technology in food industry, Meat Ind. 09 (1999) 43–45, in Chinese.
[51] H.-R. Ju, C.-G. Liu, Application of ultrasonic in wine brewing, China Brew. 01 (1997) 35–36, in Chinese.
[52] K.S. Ojha, T.J. Mason, C.P. O'donnell, J.P. Kerry, B.K. Tiwari, Ultrasound technology for food fermentation applications, Ultrason. Sonochem.34, (2017), 410-417.
[53] D. Novoa-Díaz, J.M. Rodríguez-Nogales, E. Fernández-Fernández, J. Vila-Crespo, J. García-Álvarez, Ultrasonic monitoring of malolactic fermentation in red wines, Ultrason. 54 (6) (2014) 1575–1580.
[54] C. Stillhart, M. Kuentz, Comparison of high-resolution ultrasonic resonator technology and Raman spectroscopy as novel process analytical tools for drug quantification in self-emulsifying drug delivery systems, J. Pharm. Biomed. Anal. 59 (2012) 29–37.
[55] N. Masuzawa, A. Kimura, E. Ohdaira, Ultrasonic monitoring of the progress of lactic acid fermentation, Jpn. J. Appl. Phys. 42 (5) (2003) 2963–2964.
[56] D.J. Mcclements, S. Gunasekaran, Ultrasonic characterization of foods and drinks: Principles, methods, and applications, Crit. Rev. Food Sci. Nutr. 37 (1) (1997) 1–46.
[57] M.A. Amer, D. Novoa-Díaz, A. Puig-Pujol, J. Capdevila, J.A. Chávez, A. Turó, M. J. García-Hernández, J. Salazar, Ultrasonic velocity of water–ethanol–malic acid–lactic acid mixtures during the malolactic fermentation process, J. Food Eng. 149 (2015) 61–69.
[58] P. Resa, L. Elvira, F.M.D. Espinosa, Y. Gómez-Ullate, Ultrasonic velocity in water-ethanol-sucrose mixtures during alcoholic fermentation, Ultrason. 43 (4) (2005) 247–252.

[59] S. Hoche, M.A. Hussein, T. Becker, Critical process parameter of alcoholic yeast fermentation: speed of sound and density in the temperature range 5–30 °C, Int. J. Food Sci. Technol. 49 (2014) 2441–2448.
[60] D. Geier, K. Heermann, M. Hussein, T. Becker, Effects of yeast and maltose concentration on ultrasonic velocity and attenuation coefficient and its application for process monitoring, Eng. Life Sci. 14 (2014) 433–441.
[61] A. Morata, I. Loira, R. Vejarano, C. González, M. Jesús, Emerging preservation technologies in grapes for winemaking, Trends Food Sci. Technol. 67 (2017) 36–43.
[62] M.M. Hasan, H.K. Yun, E.J. Kwak, K.H. Baek, Preparation of resveratrol-enriched grape juice from ultrasonication treated grape fruits, Ultrason. Sonochem. 21 (2) (2014) 729–734.
[63] E.J. Bartowsky, Bacterial spoilage of wine and approaches to minimize it, Lett. Appl. Microbiol. 48 (2) (2010) 149–156.
[64] E.J. Bartowsky, P.A. HEnschke, Acetic acid bacteria spoilage of bottled red wine - A review, Int. J. Food Microbio. 125(1), (2008), 60-70.
[65] H. Luo, F. Schmid, P.-R. Grbin, V. Jiranek, Viability of common wine spoilage organisms after exposure to high power ultrasonics, Ultrason. Sonochem. 19 (3) (2012) 415–420.
[66] C.-H. Dai, F. Xiong, R.-H. He, W.-W. Zhang, H.-L. Ma, Effects of low-intensity ultrasound on the growth, cell membrane permeability and ethanol tolerance of *Saccharomyces cerevisiae*, Ultrason. Sonochem. 36 (2017) 191–197.
[67] F. Xiong, The Influence of Low Intensity Ultrasonic Irradiation Treatment on the Proliferation and Fermentation Efficiency of *Saccharomyces cerevisiae*, Jiangsu University, Zhenjiang, 2017 in Chinese.
[68] H.-S. Hong, M.-L. Zhu, W. Li, H.-M. Guo, Optimization of fermentation process and physicochemical properties of probiotic fermented grape pomace, Food Sci. 40 (8) (2019) 63–72, in Chinese.
[69] K. Matsuura, M. Hirotsune, Y. Nunokawa, M. Satoh, K. Honda, Acceleration of cell growth and ester formation by ultrasonic wave irradiation, J. Ferment. Bioeng. 77 (1) (1994) 36–40.
[70] R.O. Simancas, M. Díaz-Maroto, M. Pardo, P.P. Porras, M. Pérez-Coello, Effect of power ultrasound treatment on free and glycosidically-bound volatile compounds and the sensorial profile of red wines, Molecules 26 (4) (2021) 1193–1199.
[71] Y. Cui, W. Lv, J.-F. Liu, B.-J. Wang, Effect of different ending fermentation technologies on microbial-stability of Italian riesling low alcohol sweet white wine, Adv. Mat. Res. 393 (2012) 1165–1168.
[72] L. Gracin, A.R. Jambrak, H. Juretić, S. Dobrović, I. Barukčić, M. Grozdanović, G. Smoljanić, Influence of high power ultrasound on Brettanomyces and lactic acid bacteria in wine in continuous flow treatment, Appl. Acoustics 103 (2015) 143–147.
[73] N. Dermot, Ultrasound for accelerating the wine ageing process: a winetaster's view, in: Applications of Ultrasound in the Beverage Industry, Nova Science Publishers, New York, 2016, pp. 111–114.
[74] V.L. Singleton, D.E. Draper, Ultrasonic treatment with gas purging as a quick aging treatment for wine, Am. J. Enol. Vitic. 14 (1) (1963) 23–35.
[75] J.F. García Martín, Q.-A. Zhang, C.-H. Feng, Ultrasound wine ageing from physicochemical point of view, in: Applications of Ultrasound in the Beverage Industry, Nova Science Publishers, New York, 2016, pp. 89–110.
[76] F. Zhao, Study on Aging Technology of Dry Red Wine, Hebei Agricultural University, Baoding, 2008 in Chinese.
[77] Q.-A. Zhang, T.-T. Wang, Effect of ultrasound irradiation on the evolution of color properties and major phenolic compounds in wine during storage, Food Chem. 234 (1) (2017) 372–380.
[78] Y. Tao, J.F. García Martín, D.-W. Sun, Advances in wine aging technologies for enhancing wine quality and accelerating wine aging process, Crit. Rev. Food Sci. Nutr. 54 (6) (2014) 817–835.
[79] E. Puertolas, G. Saldana, S. Condon, I. Alvarez, J. Raso, Evolution of polyphenolic compounds in red wine from Cabernet Sauvignon grapes processed by pulsed electric fields during aging in bottle, Food Chem. 119 (3) (2010) 1063–1070.
[80] A.-C. Chang, The effects of gamma irradiation on rice wine maturation, Food Chem. 83 (3) (2003) 323–327.
[81] Q.-A. Zhang, Y. Shen, X.-H. Fan, J.F. García Martín, Preliminary study of the effect of ultrasound on physicochemical properties of red wine, CyTA-J. Food 14 (1) (2016) 55–64.
[82] Q.-A. Zhang, Y. Shen, X.-H. Fan, J.F. García Martín, X. Wang, Y. Song, Free radical generation induced by ultrasound in red wine and model wine: an EPR spin-trapping study, Ultrason. Sonochem. 27 (2015) 96–101.
[83] Q.-A. Zhang, X.-H. Fan, J.-F. Yuan, Progress of accelerated red wine ageing technique mediated by ultrasound treatment, Food Ferment. Ind. 40 (1) (2014) 143–147, in Chinese.
[84] N. Masuzawa, E. Ohdaira, M. Ide, Effects of ultrasonic irradiation on phenolic compounds in wine, Jpn. J. Appl. Phys. 39 (1) (2000) 2978–2979.
[85] K. Matsushita, M. Nishina, T. Asakura, S. Kamei, M. Suzuki, K. Yabe, Physical aging by soft ultrasonic wave enhances ethanol metabolism: metabolic process of wine as followed by 400 MHZ 1H-NMR spectroscopy, Physiol. Chem. Phys. Med. NMR. 32 (1) (2000) 13–19.
[86] A. Nose, M. Hojo, Hydrogen bonding of water-ethanol in alcoholic beverages, J. Biosci. Bioeng. 102 (4) (2006) 269–280.
[87] F. Ren, S.-Q. Qiu, Artificial ageing of liquor, Liquor-Making Sci. Technol. 204 (6) (2011) 80–82, in Chinese.
[88] Y. Tao, Z. Zhang, D.-W. Sun, Experimental and modeling studies of ultrasound-assisted release of phenolics from oak chips into model wine, Ultrason. Sonochem. 21 (5) (2014) 1839–1848.
[89] B.-R. Hu, W. Wen, S.-Z. Yin, Y. Zhu, F.-M. Zhang, Analysis of DPPH scavenging capacity of dry red wine and its relationship with total phenol content by electron paramagnetic resonance spectroscopy, China Agric. Sci. 45 (01) (2012) 135–141, in Chinese.
[90] M. S. Fernández-Pachón, D. Villaño, M.C. García-Parrilla, A.M. Troncoso, Antioxidant activity of wines and relation with their polyphenolic composition, Anal. Chim. Acta., 513(1), (2004), 113-118.
[91] Y. Shen, Q.-A. Zhang, X. Yi, X.-L. Zhang, Y.-Y. Yan, Effects of ultrasonic treatment on the content of total phenols, total flavonoids and free radical scavenging activity of red wine, Food Ind. Sci. Technol. 36 (23) (2015) 111–115, in Chinese.
[92] J. Shu, D.-H. Liu, G.-F. Xie, Research advance on ultrasonic aging of wine products, Food Nutrit. China 17 (9) (2011) 56–59, in Chinese.
[93] E. Celotti, S. Stante, P. Ferraretto, T. Román, A. Natolino, High power ultrasound treatments of red young wines: effect on anthocyanins and phenolic stability indices, Foods 9 (10) (2020) 1344–1356.
[94] X.-H. Li, The Study of the Color and Anthocyanins in Red Wine Promoted by Ultrasound Treatment, Guangdong University of Technology, Guangzhou, 2017 in Chinese.
[95] Q.-A. Zhang, X.-Z. Fu, J.F. García Martín, Effect of ultrasound on the interaction between (-)-epicatechin gallate and bovine serum albumin in a model wine, Ultrason. Sonochem., 37, (2017), 405–413.
[96] L. Liu, I. Loira, A. Morata, J.A. Suárez-Lepe, M.C. González, D. Rauhut, Shortening the ageing on lees process in wines by using ultrasound and microwave treatments both combined with stirring and abrasion techniques, Eur. Food Res. Technol. 242 (4) (2016) 559–569.
[97] J.F. García Martín, L. Guillemet, C. Feng, D.-W. Sun, Cell viability and proteins release during ultrasound-assisted yeast lysis of light lees in model wine, Food Chem. 141 (2) (2013) 934–939.
[98] M.D.F. Juan, I. Loira, A. Morata, C. Gonzalez, J. Antonio Suarez-Lepe, R. Cuerda, Application of ultrasound to improve lees ageing processes in red wines, Food Chem. 261 (30) (2018) 157–163.
[99] M. J. Delgado-González, M.M. Sánchez-Guillén, M.V. García-Moreno, M.C. Rodríguez-Dodero, C. García-Barroso, D.A. Guillén- Sánchez, Study of a laboratory-scaled new method for the accelerated continuous ageing of wine spirits by applying ultrasound energy, Ultrason. Sonochem., 36, (2017), 226–235.
[100] Y.-Y. Yan, T.-T. Wang, X.-Z. Fu, C.-X. Wei, X.-H. Fan, Q.-A. Zhang, On line monitoring of conductivity of model wine induced by ultrasound and its relationship with Fe^{2+}/ Fe^{3+}, Food Mach. 33 (1) (2017) 22–26, in Chinese.
[101] G.Y. Kreitman, A. Cantu, A.L. Waterhouse, R.J. Elias, Effect of metal chelators on the oxidative stability of model wine, J. Agric. Food Chem. 61 (39) (2013) 9480–9487.
[102] Z.-D. Xue, Q.-A. Zhang, H.-R. Zheng, Roles of free radical on the formation of acetaldehyde in model wine solutions under different ultrasound parameters: A key bridge-link compound for red wine coloration during ageing, Ultrason. Sonochem. 79 (2021), 105757.
[103] Z.-D. Xue, Q.-A. Zhang, T.-T. Wang, Co-pigmentation of caffeic acid and catechin on wine color and the effect of ultrasound in model wine solutions, J. AOAC Int. 104 (6) (2021) 1703–1709.
[104] X.-Z. Fu, Q.-A. Zhang, B.-S. Zhang, P. Liu, Effect of ultrasound on the production of xanthylium cation pigments in a model wine, Food Chem. 268 (2018) 431–440.
[105] B.-Y. Chen, Q.-A. Zhang, B.-S. Zhang, Y.-F. Zhang, E.-C. Li, Effects of ultrasound on the formation of oxidative pigments in a model red wine solution containing glutathione, J. Food Compos. Anal. 103 (2021), 104092.
[106] K. Lukić, M. Brnčić, N. Ćurko, M. Tomašević, K. Ganić, Effects of high power ultrasound treatments on the phenolic, chromatic and aroma composition of young and aged red wine, Ultrason. Sonochem. 59 (2019), 104725.
[107] C. Sánchez-Córdoba, E. Durán-Guerrero, R. Castro, Olfactometric and sensory evaluation of red wines subjected to ultrasound or microwaves during their maceration or ageing stages, LWT- Food Sci. Technol. 144 (2021), 111228.
[108] K. Lukić, M. Brnčić, N. Ćurko, M. Tomašević, A.J. Tušek, K. Ganić, Quality characteristics of white wine: The short- and long-term impact of high power ultrasound processing, Ultrason. Sonochem. 68 (2020), 105194.
[109] Q.-A. Zhang, B.-W. Xu, B.-Y. Chen, B.-S. Zhang, S. Cheng, Changes of wine flavor properties from the decreased higher alcohols induced by ultrasound irradiation, Sci. Agric. Sin. 54 (8) (2021) 1772–1786, in Chinese.
[110] Q.-A. Zhang, B.-W. Xu, B.-Y. Chen, W.-Q. Zhao, C.-H. Xue, Ultrasound as an effective technique to reduce higher alcohols of wines and its influencing mechanism investigation by employing a model wine, Ultrason. Sonochem. 61 (2020), 104813.
[111] Q.-A. Zhang, H.-R. Zheng, S. Cheng, B.-W. Xu, P.-H. Guo, Comparison of ultrasound type and working parameters on the reduction of four higher alcohols and the main phenolic compounds, Sustainability 14 (2022) 417–433.
[112] F. Chemat, M.-K. Khan, Applications of ultrasound in food technology: Processing, preservation and extraction, Ultrason. Sonochem. 18 (4) (2011) 813–835.
[113] Y. Cui, W. Lv, R.-X. Fu, Z.-H. Huang, Comparison of ultrasonic and microwave treatment on shortening the aging period of red wine, Food Res. Dev. 38 (09) (2017) 118–121.
[114] M. Zenker, V. Heinz, D. Knorr, Application of ultrasound-assisted thermal processing for preservation and quality retention of liquid foods, J. Food Prot. 66 (9) (2003) 1642–1649.
[115] Z.M. Baboli, L. Williams, G. Chen, Design of a batch ultrasonic reactor for rapid pasteurization of juices, J. Food Eng. 268 (19) (2019), 109736.
[116] C. Jayani, O. Christine, K. Sandra, A. Muthupandian, A. Review, Ultrasonics in food processing, Ultrason. Sonochem. 19 (2012) 975–983.
[117] D. Knorr, M. Zenker, V. Heinz, D.U. Lee, Applications and potential of ultrasonics in food processing, Trends Food Sci. Technol. 15 (5) (2004) 261–266.
[118] A. Williams, New technologies in food preservation and processing: Part I, Nutr. Food Sci. 93 (6) (1993) 16–19.

[119] C.E. Leadley, A. Williams, J.G. Brennan, Pulsed electric field processing, power ultrasound and other emerging technologies. Food Processing Handbook. New York: Wiley, (2006), pp: 201-235.
[120] E. Joyce, S.S. Phull, J.P. Lorimer, T.J. Mason, The development and evaluation of ultrasound for the treatment of bacterial suspensions. A study of frequency, power and sonication time on cultured Bacillus species, Ultrason. Sonochem. 10 (6) (2003) 315–318.
[121] R. Pagán, P. Manas, I. Alvarez, S. Condón, Resistance of Listeria monocytogenes to ultrasonic waves under pressure at sublethal (manosonication) and lethal (manothermosonication) temperatures, Food Microbiol. 16 (2) (1999) 139–148.
[122] A. Bevilacqua, B. Speranza, D. Campaniello, M. Sinigaglia, M.R. Corbo, Inactivation of spoiling yeasts of fruit juices by pulsed ultrasound, Food Bioprocess Technol. 7 (8) (2014) 2189–2197.
[123] A. Bevilacqua, D. Campaniello, M. Sinigaglia, M.R. Corbo, Combination of ultrasound and antimicrobial compounds towards Pichia spp. and Wickerhamomyces anomalus in pineapple juice, LWT-Food Sci. Technol. 64 (2) (2015) 616–622.
[124] W. Lv, F.-Q. Zhang, Y. Cui, Effect of several treatments on fermentation and quality of low alcohol white wine, China Brew. 31 (05) (2012) 74–77, in Chinese.