Review

Prospects and application of ultrasound and magnetic fields in the fermentation of rare edible fungi

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\textbf{ABSTRACT}

Ultrasound has the potential to be broadly applied in the field of agricultural food processing due to advantages such as environmental friendliness, low energy costs, no need for exogenous additives and ease of operation. High-frequency ultrasound is mainly used in medical diagnosis and in the food industry for the identification of ingredients and production line quality testing, while low-frequency ultrasounds is mainly used for extraction and separation, accelerating chemical reactions, auxiliary microbial fermentation and quality enhancement in food industry. Magnetic fields have many advantages of convenient use, such as non-toxic, nonpolluting and safe. High-intensity pulsed magnetic fields are widely used as a physical non-thermal sterilization technology in food processing, while weak magnetic fields are better at activating microorganisms and promoting their growth. Ultrasound and magnetic fields, due to their positive biological effects, have a wide range of applications in the food processing industry. This paper provides an overview of the research progress and applications of ultrasound and magnetic fields in food processing from the perspectives of their biological effects and mechanisms of action. Additionally, with the development and application of physical field technology, physical fields can now be used to provide significant technical advantages for assisting fermentation. Suitable physical fields can promote the growth of microbial cells, improve mycelial production and increase metabolic activity. Furthermore, the current status of research into the use of ultrasound and magnetic field technologies for assisting the fermentation of rare edible fungi, is discussed.

\section{1. Introduction}

The use of physical fields such as sound, light, electricity, magnetism and force in food processing can help avoid the food safety problems, destruction of nutrients and environmental pollution caused by high temperatures in traditional processing and by excessive use of chemical solvents. Physical fields can significantly improve food processing efficiency and food quality by enhancing the mass transfer effect and by changing the structure of biomolecules and their physicochemical properties. The appropriate application of physical fields in fermentation engineering can improve microbial fermentation efficiency. In-depth research on the basic theory of physical fields and the improvement and optimization of technical parameters has allowed for the development and application of corresponding processing equipment. Since these advancements have occurred, the positive biological effects associated with using ultrasound and magnetic fields in food processing have attracted widespread research attention. This paper provides an overview of the biological effects of and mechanisms underlying ultrasound and magnetic field food processing technologies. Furthermore, this paper covers the application of the two technologies for assisting the fermentation of rare edible fungi. These discussions should provide a reference for promoting the industrial application of ultrasound and magnetic field technologies.

\section{2. Physical fields}

\subsection{2.1. Ultrasound}

Ultrasound is a sound wave that propagates through a propagation medium at frequencies between 20 kHz and 1 GHz; the human ear cannot respond to these frequencies as they are too high [1,2]. According to the power density, ultrasound can be divided into low-
intensity (<1 W/cm²) and high-intensity (10–1000 W/cm²) ultrasound [2]. Depending on the power frequency, ultrasound can be classified as high power low frequency (20–100 kHz), medium power medium frequency (100 kHz–1 MHz) or low power high frequency (1–100 MHz) [1]. According to the different working modes, ultrasound can be classed as sweep or fixed frequency, pulse or continuous, multi-frequency or single frequency, sequential multi-frequency or synchronous multi-frequency, counter-current circulation or non-forced flow, and contact or non-contact [3].

Several review articles and textbook chapters describe ultrasound technology for food applications [4-6]. Ultrasound has the potential to be broadly applied in the field of agricultural food processing due to advantages such as environmental friendliness, low energy costs, no need for exogenous additives and ease of operation. High-frequency ultrasound that is non-destructive, non-invasive, fast and accurate amongst other characteristics, is mainly used in medical diagnosis and in the food industry for the identification of ingredients and production line quality testing [7,8]. Low-frequency ultrasound, as a non-thermal physical processing technique, has low energy consumption and reduced processing time and thermal effects. Thus, low-frequency ultrasound can improve cell membrane permeability [8], enhance material transfer and modify molecular structures [9–12]. Therefore, low-frequency ultrasound is mainly used for extraction and separation [13–15], accelerating chemical reactions [16], freezing [17], thawing [18], drying [19], defoaming and degassing [19], homogenization [20], emulsification [21], passivation of enzyme activity [21] and inactivation of microorganisms [22]. In the food industry, low-frequency ultrasound has been used effectively for aging and maturation [23], pesticide residue elution [22], food cleaning and sterilization [24], osmotic dehydration [25], auxiliary enzymatic catalysis [26], auxiliary microbial fermentation (Fig. 1) [27,28], auxiliary non-enzymatic reactions [29], quality enhancement [30], flavor improvement [26,29,31,32], active substance encapsulation [33] and membrane bioreactors cleaning [34,35].

2.2. Magnetic fields

A magnetic field is a physical field that transmits the interaction between, and is created by, moving charges or electric currents. Magnetic fields are classified into static and dynamic, and uniform and non-uniform fields. Constant magnetic fields are called static magnetic fields, while alternating and pulsating magnetic fields are dynamic magnetic fields. A magnetic field with equal or approximately equal intensity in all parts of the space is called a uniform magnetic field. If this is not the case, the field is called a non-uniform magnetic field (Table 1). According to the effect of magnetic fields on organisms, magnetic fields are classified into different intensity levels: weak (<1 T), strong (1–5 T) and ultra-strong (>5 T). Weak magnetic fields are better at activating microorganisms and promoting their growth [37-39]. Strong magnetic fields kill microorganisms [40].

High-intensity pulsed magnetic fields are widely used as a physical non-thermal sterilization technology in food processing [41-45]. This technology overcomes the side effects of heat sterilization on the flavor and nutrient contents of products, and the toxic side effects of chemical non-thermal sterilization reagent residues on the human body. High-intensity pulsed magnetic fields show unique superiority in the processing of juices, milk and other foods. High-intensity pulsed magnetic fields destroy the structure of microbial cells and hinder their normal physiological activities. This technology is associated with a short sterilization time and low energy consumption, and is better for maintaining the original nutrients and flavor substances in the food [45]. The non-thermal biological effect of weak magnetic fields is achieved via the electromagnetic waves having a triggering effect on microorganisms. This affects the metabolic energy of the biological system itself, changes the structural characteristics of biological cells [46,47], affects the

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**Table 1**

Classification of magnetic fields adapted from Zhou [50].

| Magnetic field type | Features | Graphics | Examples |
|--------------------|----------|----------|----------|
| Constant magnetic field | Magnetic field strength and direction are constant | Magnetic field strength and direction are constant | Eternal Magnets |
| Alternating magnetic field | Magnetic field strength, direction regular change | Magnetic field strength, direction regular change | Industrial frequency magnetic therapy machine |
| Pulsating magnetic field | The magnetic field strength varies regularly and the direction is constant | Magnetic field strength varies regularly and the direction is constant | Co-polar rotating magnet therapy, magnetic field generated by pulsating DC magnets |
| Pulsed magnetic field | Intermittent emergence of magnetic fields | Intermittent current flow into the coil of an electromagnet with various shapes of pulsed magnetic fields | |

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**Fig. 1.** Sweeping multi-frequency ultrasound slot equipment and fermentation system adapted from Zhang [36]. 1, ultrasonic generator; 2, ultrasonic transducer; 3, slot chamber; 4, inlet port; 5, sampling port; 6, sterilization vent; 7, pressure gauge; 8, outlet port; 9, condenser; 10, peristaltic pump; 11, fermentation bottle; 12, constant temperature stirring water bath.
chemical bonds and molecular conformation of nucleic acids, proteins and biological macromolecules [48,49], and affects free radical activity [50]. The biological effects caused by magnetic fields are affected by multiple factors, such as frequency range, field strength range and material handling conditions. For example, high-intensity pulsed magnetic field sterilization technology results in a “biological window effect” [51,52]; magnetic induction strength and enzymatic reaction rate does not show a linear relationship [53], but inhibition and promotion alternately. Although the mechanisms underlying magnetic effects have not been thoroughly revealed, magnetic fields have been used in medical aid therapy [54-57] and in the food industry for sterilization [24,43,58-61], passivation of enzyme activity [45,62], preservation of fruits and vegetables [63-66], auxiliary microbial fermentation (Fig. 2) [67-70], improvement of seed growth and physiological properties [71], and reduction of microbial adsorption of heavy metals [82]. Other research fields have used magnetic fields for a wide range of applications [83,84].

3. Physical field technology characteristics and mechanisms of action

3.1. Ultrasonic field technology characteristics

Ultrasonic has cavitation, mechanical and thermal effects [85-87] (Fig. 3). The ultrasonic cavitation effect refers to the nucleation of tiny bubbles in the liquid under the action of ultrasonic waves, and to a series of kinetic processes such as bubble nucleus oscillation, growth, contraction and collapse. Ultrasonic cavitation is divided into steady-state cavitation (acoustic pressure less than 10 W/cm²) and transient cavitation (acoustic pressure greater than 10 W/cm²). Steady-state cavitation subjects cells or biological macromolecules to the shear stress generated by microacoustic flow and the osmotic dynamics generated by the secondary electro-optical effect of cavitation, and thus intensifies biochemical processes. Transient cavitation generates high temperature and high pressure (7000–16000 K and 5 × 10⁷ Pa) in the cell, while generating strong redox radicals and potential, which can destroy cell structures or break cells, leading to macromolecular damage or cell death [88]. Ultrasonic mechanical effects refer to how the propagation of ultrasonic waves in the medium cause the medium mass to vibrate, accelerating the mass–liquid transfer process and promoting biological mass transfer. This mechanical force can prompt the substrate to enter the active site of microbial catalysts, enhance the affinity between substrate and enzymes, and improve the speed of biological reactions. However, stronger ultrasonic intensities can also damage the structure of biological macromolecules in culture media (such as fermentation broths) and cause other biological effects, such as the mutation of genetic traits. The ultrasonic thermal effect refers to how the vibration energy of the ultrasonic wave is continuously absorbed by the propagation medium and converted to heat energy, which increases the temperature of the medium. The thermal effect can provide an ideal reaction environment for substrate–enzyme reactions [89,90]. However, when the rate of thermal energy deposition exceeds thermal diffusion or conduction in the tissue, the temperature increase causes the denaturation and inactivation of intracellular molecules [87,91,92]. Therefore, organisms respond to ultrasound effects at low intensities and suitable frequency conditions, but there is also a stress response to acousto-photothermal and chemical factors, such as high frequency, high pressure and high temperature, caused by different ultrasound conditions. The applications and mechanisms of action of low-frequency ultrasound in the food industry are listed in Table 2.

3.2. Mechanism of action of low-frequency ultrasound fields

The positive biological effects caused by low-frequency ultrasound include (1) changes in cell membrane permeability and increased cell growth rate; (2) changes in molecular conformation and intensification of reaction processes; and (3) activation of intracellular signal transduction systems and changes to the synthesis of metabolites within the organism.

The cavitation, mechanical and thermal effects of ultrasound all lead to positive changes in cell membrane permeability. Firstly, via the cavitation effect, the interaction between the cavitation bubble and the cell membrane (push–pull effect) can increase the permeability of the cell membrane [4]; the electrical effect produced by cavitation can change the surface potential of the cell membrane, and the osmotic force increases the cell membrane permeability [106]. Secondly, a microjet shear force is generated by ultrasonic cavitation and by the mechanical effect of the acoustic radiation. This force acts on the cell, forming a cavity on the surface of the cell membrane, which increases the permeability of the cell membrane. Thirdly, via the thermal effect, cells absorb the ultrasonic energy and the temperature of biological tissues increases; this leads to increases in the fluidity and permeability of cytoplasmic membranes [107]. The formation of cell membrane cavities and increases in fluidity accelerate the transport and exchange of substances inside and outside the cell, promote cell growth and reproduction, and increase metabolite production. Meanwhile, the electrical potential also accelerates the activation of calcium channels, increases the intracellular Ca²⁺ concentration, and shortens the growth cycle of cells [108].

When used in food processing, ultrasonic cavitation and mechanical effects affect the fermentation culture substrate, enzymatic substrate, biocatalyst, and metabolite molecular structure. These ultrasonic effects also improve the reaction system environment, enhance the reaction efficiency, and strengthen the reaction process. Firstly, with respect to the effects of ultrasound on substrates, ultrasound can promote the release of large substrate active sites in fermentation or enzymatic substrates. This is achieved through mild physical denaturation, such as protein defolding and peptide fragment targeting, and enhances substrate nutrient utilization and metabolite enrichment [109]. With respect to the effects of ultrasound on biocatalysts, ultrasound can regulate the enzyme active center, improve the distribution of groups and intermolecular forces of the biocatalyst, reduce the number of irregular curls in the molecular structure, promote the formation of the highly active transition state of enzymes, and improve the affinity between the substrate and enzyme [90]. With respect to the effects of the ultrasound on products and reaction processes, mechanical mass transfer effects promote product diffusion and extracellular transfer. Product release and mechanical mass transfer further intensify the kinetic reactions of substrates and products [110,111]. Ultrasonic effects also promote the formation of specific functional groups and molecular structures in the products and influence the properties and activities of the products [112,113]. Furthermore, in terms of how ultrasound can improve the reaction system environment, ultrasonic cavitation increases the number of bubbles in the medium, which increases the exchange space of gas and liquid and increases the amount of dissolved

![Fig. 2. Schematic diagram of low-frequency alternating magnetic field equipment](image-url)
oxygen in the medium [114]. At the same time, the rapid rupture of cavitation bubbles produces an environment that is characterized by free radical oxidation, high temperature and pressure, and accelerated chemical reactions [115].

The cavitation, mechanical and thermal effects of ultrasound affect the expression of genes associated with metabolic synthesis pathways of organisms, mostly in the context of defense responses to stressful environments. Ultrasound activates signaling molecules in the organism, which, upon binding to intracellular receptors, become transcriptional promoters that act on specific regulatory sequences to initiate gene transcription and expression, and to synthesize metabolites [116].

When ultrasound acts on an organism, the multiple biophysical effects produced can lead to the intensification of biological processes through different mechanisms. Appropriate ultrasound conditions can promote the growth of microbial cells and the synthesis of beneficial metabolites as described above. However, when ultrasound reaches a certain dose, the cavitation, mechanical and thermal effects generate high temperatures, high pressure and free radicals. These can cause cell structure destruction and shearing of biological macromolecules or conformational changes that cause irreversible damage, thus inhibiting biological processes. Thus, these high ultrasonic doses are mostly used for processes such as auxiliary sterilization and blunting enzyme activity. In addition, the ultrasonic cavitation effect and its secondary effects, or high pressure and high frequency transient mechanical effects, can be used to shear genes and change protein expression levels to achieve mutagenic breeding.

3.3. Magnetic field technology characteristics

The responses of biological systems to magnetic fields, which can also be described as the biological effects of electromagnetic waves, can be divided into thermal and non-thermal effects. The thermal effects are caused by the temperature changes caused due to Joule heating by the electromagnetic waves entering the biological system. The non-thermal effects are directly caused by the electromagnetic waves entering the biological system. In other words, the thermal effects are caused by the energy carried by the electromagnetic waves, while the non-thermal effects are caused by the information carried by the electromagnetic waves.

The biological effects of magnetic fields are characterized by the window effect, magnetic field strength threshold, hysteresis and synergism. The window effect refers to how an organism only responds to a particular strength of magnetic field. Further, the magnetic field must be within a certain range or strength threshold to cause biological effects. The term hysteresis is used to describe how a period of time must elapse before the organism exhibits the corresponding magnetic field effect. Finally, synergism describes how a very weak applied magnetic field can stimulate a very strong biological response. The applications and mechanisms of action of magnetic field technology in the food industry are listed in Table 3.

3.4. Mechanism of action of weak magnetic fields

The biological effects of weak magnetic treatments are mainly due to the affects the treatment has on the medium properties, physicochemical properties of cell membranes, structure of biological macromolecules, and free radicals. Magnetic fields can produce positive biological effects by influencing several aspects of media parameters, cell morphology structure, enzyme activity [118,119] and gene expression [130-133].

3.4.1. Effect of magnetic field treatment on the medium

Magnetic field treatment changes the properties of the culture medium. For example, it has been shown that increasing the strength of the magnetic field treatment reduces the conductivity of Spirulina culture solution and increases the NO$_3$-N content; this facilitates cellular uptake and metabolism [134]. However, it has also been suggested that magnetic fields do not increase the consumption of nitrogen by cells and are not responsible for increasing cell growth. The nitrate that is absorbed by cells through the active transport system is reduced to nitrite by nitrate reductase, and then to ammonium by nitrite reductase. In cells
containing high concentrations of ribulose-1,5-bisphosphate-carboxylase/oxygenase (Rubisco), large amounts of nitrogen and sulfur, which are necessary for cell growth, are consumed to produce the enzyme. Magnetic field treatment alters the protein profile but does not change the energy level and spin direction of electrons in the medium. In addition, magnetic forces alter ion exchange, and the changes in ion exchange can affect medium consumption [135]. Magnetic fields may change the enzyme. Magnetic field treatment alters the protein profile but does not change the pH of the medium [136]. The use of magnetic field-treated water (magnetized water) for the cultivation of Cordyceps militaris, and the synergistic effect of magnetized water and selenium ions in the medium, has been shown to trigger a series of physiological and biochemical changes [137]. Magnetized water has significant effect on the extracellular enzyme activity (protease, polyphenol oxidase and amylase), mycelial growth and medicinal ingredients (D-mannitol and

| Applications | Mechanism of action | Reference |
|--------------|---------------------|-----------|
| Auxiliary separation and extraction | Accelerates mass transfer and increases the rate of component dissolution. | [14,93] |
| Auxiliary enzymatic catalysis | Changes the molecular conformation of substrate and enzyme, promotes the contact between substrate and enzyme, and enhances the reaction. | [26,94] |
| Auxiliary microbial fermentation | Improves microbial morphology, activity and rheological properties of fermentation broth. | [27,95, 28,34] |
| Auxiliary membrane filtration, membrane separation | Cavitation effect (microjet) and mechanical effect to break the concentration difference of deposited particles on both sides of the membrane. | [34,35] |
| Defoaming, degassing | Accelerates bubble aggregation, enlargement and rupture. | [96,97] |
| Emulsification, homogenization | Reduces the particle size and molecular mass of biomolecules and increases solubility. | [21,32] |
| Osmotic dehydration, drying | Accelerates the vibration and migration of water molecules, increases the rate of water diffusion, and increases the mass transfer driving force. | [19,98-100] |
| Auxiliary freezing | Caviation bubbles act as nuclei to promote ice crystal formation, and the shear forces generated by caviation reduce the size of ice crystals and accelerate the freezing rate. | [17] |
| Auxiliary thawing | The microjet formed by caviation bubble rupture increases the flow velocity of thawing medium, accelerates the heat exchange between thawing material and medium, and strengthens the convective heat transfer effect. | [18] |
| Pesticide residue elution | The strong oxidizing ability of free radicals generated by caviation accelerates the emulsification of fat-soluble components, exposes their hydrophilic groups and degenerates them into the water; or reduces the adhesion of pesticide residues on food and agricultural products through the mechanical effect. | [101] |
| Auxiliary cleaning and sterilization | The cavitation effect produces high temperature and high pressure to destroy the cell wall or cell membrane of bacteria; the free radicals with strong oxidizing properties are produced to destroy the DNA of microbial cells and inactivate enzymes to kill bacteria. | [102] |
| Aging and maturation | The cavitation effect generates hydroxyl radicals, and the number of molecules with hydrogen bonding increases, and the hydrogen bonds between molecules are broken, accelerating various chemical reactions such as esterification and oxidation. | [103] |
| Auxiliary mutagenesis breeding | The high temperature and pressure generated by the cavitation effect shear biological macromolecules such as DNA and proteins and change the molecular conformation. | [104] |
| Auxiliary non-catalytic reactions | The high temperature and pressure generated by the cavitation effect promote the unfolding of molecular structures, intensify the collision of reactive groups, and accelerate the reaction process. | [29] |
| Flavor improvement | Enhances the biosynthesis of valuable metabolites (secondary) by stimulating the activity of plant cells (physiological). | [31] |
| Meat tenderization | Disrupts the integrity of myocytes or enhances the interaction of free radical acoustic chemical reaction products with the meat protein matrix. | [105] |

**Table 3**

Applications and mechanisms of action of magnetic field technology in the food industry.

| Applications | Mechanism of action | Reference |
|--------------|---------------------|-----------|
| Auxiliary separation and extraction | The energy generated by the magnetic field is used to change the microstructure of antimagnetic substances, causing changes in the physicochemical properties and intensifying the reaction process. | [74,75,117] |
| Auxiliary/inhibited enzymatic catalysis | The enzyme active center, enzyme tertiary structure and kinetic parameters of enzymatic reactions are affected. | [118,119] |
| Auxiliary microbial fermentation | The magnetic field changes the physicochemical properties of fermentation substrate; affects the microstructure of microbial cells; accelerates the mobility of cell membrane lipids; and promotes cell growth. | [38,69,70,120-122] |
| Strain mutagenesis | The magnetic field affects the structure of cellular genetic material, causing changes in genomic DNA and regulating gene transcription and expression. | [118][123] |
| Auxiliary sterilization | The magnetic field affects the morphology of bacteria, causing cell shrinkage and leakage of contents. | [60,62,124-129] |
| Freshness preservation | The magnetic field inhibits the enzyme active center and the affinity between the enzyme and substrate. | [65] |
| Improving meat structure | The magnetic field causes increased hydrogen bonding, which affects protein structures and gel properties. | [55] |
| Improving seed growth | Magnetic field treatment improves primary metabolism. | [77] |
polysaccharide) content in submerged cultures of *C. militaris* [138].

3.4.2. Effect of magnetic field treatment on cell morphology

Magnetic field treatment affects the microstructure of the cell; it causes an acceleration of cell membrane lipid fluidity, which allows the cell to respond to external stressful stimuli and thus protect the interior of the cell. The enhanced membrane permeability increases the uptake capacity for nutrients required for microbial growth. By affecting the permeability of cell membranes and the receptor sites of proteins, magnetic fields can be used to regulate the passage of antibodies across cell membranes. Magnetic fields induce random movement of charged biomolecules in the cell and increase cell viability. Magnetic field treatment also leads to biological changes by affecting the rate of biochemical reactions, the binding of molecules to membranes, and signaling between cells, and through changes to growth rate and cell function [139].

3.4.3. Effect of magnetic field treatment on biological macromolecules

Magnetic field treatment stimulates the growth of biological organisms and may affect microbial metabolism by altering carbohydrate and protein synthesis and essential amino acid accumulation [136]. Because metabolic reactions are all based on differences in charge and systemic ions, the movement of electrons and ions may lead to changes in biomolecular concentrations (such as of proteins, carbohydrates and lipids) [140]. Changes in cell structure and morphology caused by magnetic field treatment may also lead to the breakdown of proteins into smaller peptides [136]. Magnetic field treatment can enhance microbial metabolic pathways leading to the accumulation of carbohydrates, thus stimulating growth [140]. Magnetic field treatment can interfere with enzyme kinetics and alter enzyme activity by increasing the rate of collision between biocatalysts and substrates, by altering the aggregation state of enzymes, by triggering conformational changes in enzymes, or by increasing the rate of diffusion [141].

3.4.4. Effect of magnetic field treatment on free radicals

The effect of magnetic field treatment on free radical concentrations is amplified if each radical within a pair have opposite charges. Magnetic field treatment may also induce oxidative stress in organisms by altering the energy level, electron spin orientation and radical concentration. This, thus changes the relative likelihood of recombination of other interactions and possibly produces biological effects [135].

4. Application of low-frequency ultrasound and weak magnetic fields in the fermentation of rare edible fungi

The growth period of wood-rotting edible mushroom substrates is long and susceptible to the influence of factors such as cultivation region and environmental climate, and the quality level of substrates varies. The production of rare edible mushrooms is scarce. This hinders in-depth study of the biological activities of the mushrooms. In recent years, liquid fermentation technology has provided new ideas to obtain a variety of rare edible mushrooms, such as *Phellinus igniarius* and *Ganoderma lucidum*, and their active secondary metabolites. Liquid fermentation technology is advantageous as it protects the environment, is based on short fermentation cycles, allows the acquisition of large amounts of mycelia and fermentation solution, and is easy to manage and control. More importantly, the active ingredients in the mycelium cultivated by this technology are comparable to those in the substrate. This supports the development of edible and medicinal mushroom resources and the utilization of their active ingredients, which compensates for the shortage in the market, meeting people’s needs.

With the development and application of physical field technology, physical fields can now be used to provide significant technical advantages for assisting fermentation. Physical fields have a certain degree of influence on cell morphology and structure and on biomolecular active substances. Suitable physical fields can promote the growth of microbial cells, improve mycelial production and increase metabolic activity. Both ultrasound and magnetic field techniques produce biological effects and can be applied to assist microbial fermentation. In this paper, six rare edible fungi (Grifola frondosa, Hericium erinaceus, Phellinus igniarius, Cordyceps militaris, Ganoderma lucidum and Antrodia cinnamomea; Fig. 4 (a)) were selected to provide an overview of the status of domestic and international research on the use of ultrasound and magnetic fields for assisting edible fungi fermentation.

*Grifola frondosa*, a rare medicinal fungus, has fresh, crispy seeds and tastes like shredded chicken. The dried mushrooms have a unique aroma and are rich in protein, amino acids, trace elements, vitamins and other nutritional elements. Some studies have shown that the bioactive substance of G. frondosa, G. frondosa polysaccharide, is effective in lowering blood sugar, blood lipids, and cholesterol, regulates the immunity of the body, and has anti-tumor properties. At present, liquid fermentation of *G. frondosa* is an effective and quick method used to obtain the active *G. frondosa* polysaccharide. A low-intensity alternating magnetic field has a promotional effect on the liquid fermentation of *G. frondosa*, and has been shown to significantly increase the mycelial biomass. When the magnetic induction intensity was 35 Gs, the initial magnetic treatment intervention time was 1 h after inoculation, and the duration of action was 3 h, the magnetic field had the strongest effect on the growth of the *G. frondosa* mycelium; the dry mass of the *G. frondosa* mycelium was increased by 11.43% and the total amount of all nutrients was increased. The “biological window effect” of the magnetic field on the growth of *G. frondosa* was observed at 3 h and 5 h of the magnetic field treatment [121]. The researchers investigated the cause of the window effect by analyzing the change in fermentation broth pH. The peak value of fermentation broth pH occurred at the time of the window effect of magnetic field treatment, and it was speculated that the occurrence of the window effect was related to the change of fermentation broth pH. Scanning electron microscopy was used to observe hypha morphological changes of *G. frondosa* mycelium after low intensity magnetic field treatment, and it was found that the surface of mycelium was wrinkled, mycelium was rotated, some mycelium appeared expanded and thinner, more branches were produced, and the structure of mycelium was looser. It is presumed that the mycelium produced a stress response to the magnetic field treatment. The loose structure of mycelium helps the transfer and transport of nutrients and metabolites in the fermentation broth, thus promoting the growth of mycelium and achieving the effect of magnetic field to promote fermentation.

*Hericium erinaceus*, which belongs to the subphylum Hymenomycotina, order Russulales and family Hericaceae, is a valuable food and medicinal mushroom. Polysaccharides are among the main active ingredients of *H. erinaceus*, and have anti-aging, anti-tumor, anti-mutagenesis and anti-radiation properties. These bioactive polysaccharides also function in immune system regulation and are used to treat hypoglycemia and hypolipidemia. It has been shown that a magnetic field will promote the growth of *H. erinaceus* and its extracellular polysaccharide secretion. Further, it was found that the effect of the magnetic field on the extracellular polysaccharide secretion of *H. erinaceus* had a lag relative to the effect on the mycelium. A magnetic field strength of 1.06 A/m and an action time of 12 h had the strongest growth-promoting effect on the mycelium of *H. erinaceus*, and the growth rate of the dry mass of *H. erinaceus* reached 140.1%. The growth promotion effect of the magnetic field on the extracellular polysaccharide of *H. erinaceus* was the strongest at 48 h. The rate of increase in extracellular polysaccharide mass concentration of *H. erinaceus* reached 271.7%. At 24 h, a magnetic field strength of 0.8 A/m was used to promote the production of the extracellular *H. erinaceus* polysaccharide, and the increase in extracellular polysaccharide mass concentration reached 187.5% [142]. The magnetic field treatment changed the permeability of the cell membrane of *H. erinaceus*, causing the exocytosis of intracellular polysaccharides, resulting in the senescence and death of some mycelium, as shown by the increase of mycelium biomass of *H. erinaceus* with the magnetic field treatment before 24
The magnetic field showed a promotion effect on the extracellular polysaccharide production, mainly due to the autolysis of senescent and dead cells. The promotion effect of magnetic field on the growth of *H. erinaceus* mycelium has an intensity window effect and a time window effect. It was inferred that the biological indicators were changed under a certain field strength and a certain duration of action.

*Phellinus igniarius*, a rare medicinal fungus belonging to the family Hymenochaetaceae, is rich in polysaccharides, amino acids, flavonoids, triterpene acids, aromatic acids, melanin, phenolic pigments and other chemical elements. *P. igniarius* possesses anti-tumor, antioxidant, bactericidal and immune activity regulation effects and thus has both high nutritional and medicinal value. It was found that weak magnetic field-assisted fermentation could increase the mycelial polysaccharide and flavonoid production of *P. igniarius*, and could enrich the monosaccharide composition of mycelial polysaccharides. At the same time, the weak magnetic field-assisted mode helped to improve the total antioxidant capacity and the superoxide anion radical-scavenging ability of *P. igniarius*. The maximum yield of mycelial flavonoids was 0.6918 mg/100 mL at a magnetic field strength of 120 mT, which was 2.09 times higher than that of the control. The maximum total antioxidant capacity was 10.1133 U/mL at a magnetic field strength of 180 mT, which was 55.69% higher than that of the control. The maximum scavenging capacity of superoxide anion radicals was 89.2123 U/L, which was obtained at a magnetic field strength of 90 mT and was 22.59% higher than the value obtained in the control. The weak magnetic field-assisted fermentation did not significantly change the flavonoid species of the mycelium, but did have an effect on the ratio of compounds, such as polysaccharides and proteins. There was a certain promotional effect on the protein content in the *P. igniarius* mycelia, and this effect was most obvious at the magnetic field strength of 120 mT, with an elevation of 13.81% compared with the control. The weak magnetic field-assisted fermentation of mulberry has been shown to be conducive to the enrichment of mycelial Ca, Na, and Zn elements [143]. The mycelium cells need to adapt to new environment for cell proliferation. The external stresses could cause a series of stress responses in the mycelium of the mycelium, but did have an effect on the ratio of metabolites.

*P. igniarius* and flavonoid production of *P. igniarius* field-assisted fermentation could increase the mycelial polysaccharide and flavonoid production of *P. igniarius*, and could enrich the monosaccharide composition of mycelial polysaccharides. At the same time, the weak magnetic field-assisted mode helped to improve the total antioxidant capacity and the superoxide anion radical-scavenging ability of *P. igniarius*. The maximum yield of mycelial flavonoids was 0.6918 mg/100 mL at a magnetic field strength of 120 mT, which was 2.09 times higher than that of the control. The maximum total antioxidant capacity was 10.1133 U/mL at a magnetic field strength of 180 mT, which was 55.69% higher than that of the control. The maximum scavenging capacity of superoxide anion radicals was 89.2123 U/L, which was obtained at a magnetic field strength of 90 mT and was 22.59% higher than the value obtained in the control. The weak magnetic field-assisted fermentation did not significantly change the flavonoid species of the mycelium, but did have an effect on the ratio of compounds, such as polysaccharides and proteins. There was a certain promotional effect on the protein content in the *P. igniarius* mycelia, and this effect was most obvious at the magnetic field strength of 120 mT, with an elevation of 13.81% compared with the control. The weak magnetic field-assisted fermentation of mulberry has been shown to be conducive to the enrichment of mycelial Ca, Na, and Zn elements [143]. The mycelium cells need to adapt to new environment for cell proliferation. The external stresses could cause a series of stress responses in the microorganisms, hence affecting the cell membrane permeability. When the magnetic field strength gradually increases, the cell membrane fluidity increases in order to maintain the original osmotic pressure, ion permeability, and signaling, and the increase in membrane fluidity promotes more metabolism of the cells. The intracellular polysaccharide content of the *P. igniarius* mycelium was also found to be significantly increased in the study of ultrasound-assisted liquid fermentation of *P. igniarius*. In this study, the ultrasound was applied 3.8 days after the fermentation started, with an ultrasonic action time of 65 min and a cycle of 25 s/5 s of working time/interval time. The yield of intracellular polysaccharides of the *P. igniarius* mycelium treated with ultrasound was 1.8002 g/L, which was approximately 22.64% higher than the yield in the control. Furthermore, the polysaccharides were found to have a strong in vitro antioxidant capacity [28]. The changes in cell morphology observed by laser scanning confocal microscope indicated that ultrasound could change the morphology and structure of *P. igniarius* mycelium, and accelerate the transfer of nutrients and metabolites.

*Cordyceps militaris* is a medical fungus that has various pharmacological effects. *C. militaris* is rich in cordyceps polysaccharides, cordycepin, cordycepic acid, nucleosides and other bioactive substances. These substances have important antibacterial, anti-tumor and anti-radiation properties and play a role in the regulation of immune function. The types, contents and pharmacological effects of artificially fermented Cordyceps are similar to those of wild Cordyceps. Thus, artificially fermented Cordyceps have important application value and are also significant for the conservation of Cordyceps resources. It was found that the yield of extracellular *C. militaris* polysaccharides showed an increasing trend with increasing strength of the applied magnetic field (0.015–1.500 T). The highest yield of extracellular *C. militaris* polysaccharides was observed at 1.250 T and 25 min of treatment time. However, the yield of extracellular polysaccharides of *C. militaris* was lower in the magnetic treatment group than in the control group, and the magnetic treatment inhibited the production of extracellular *C. militaris* polysaccharides [144]. Researchers have found that charged ions in a culture medium (500 mL of rice broth, containing 5 g glucose, 1 g potassium dihydrogen phosphate, 1 g magnesium sulfate, 1 g peptone, 1 g beef paste and 1 g yeast powder), such as Na\(^+\), K\(^+\) and Cl\(^-\), were affected by the magnetic field. The magnetic field changed the permeability of the biofilm to the ions and affected the metabolism, biochemical processes, and membrane potential of the microorganisms. With increasing magnetic treatment intensity, the biofilm of *C. militaris* may be partially damaged, and when in an extreme physical environment, *C. militaris* may self-protectively secrete and release extracellular polysaccharides. This may explain why the production of extracellular polysaccharides by *C. militaris* showed an increasing trend with the increase in the intensity of the applied magnetic field. Metal atoms (Fe, Mn, Co, Cu and Mo) in the activity centers of *C. militaris* enzymes are subjected to magnetism due to the magnetic field, which results in changes in enzyme activity. The magnetic field interferes with the transfer and transport of electrons or ions in the organism, leading to metabolic disorders and inhibiting the growth of the organism. These phenomena may explain why the
production of extracellular polysaccharides by *C. militaris* was lower under magnetic field treatment than in the blank control [144]. In the author’s opinion, the combination of magnetic field properties indicates that magnetic field action has a window effect. In the study of magnetic field-assisted *C. militaris* fermentation, the window effect was observed at a low magnetic field strength (0.5 T). Analysis of the mechanism underlying this window effect may further resolve the specific mechanism by which the magnetic field acts in *C. militaris* fermentation. Some researchers have also used different magnetic treatment conditions to study the biological effects generated with respect to the mycelial growth of *C. militaris*. Using the mycelial growth amount as an indicator, the optimal magnetic treatment condition to generate positive biological effects was found to be 1.25 T for 10 min [145].

*Ganoderma lucidum* has been widely used as a traditional Chinese medicine for thousands of years. Among the secondary metabolites of *G. lucidum*, triterpenes are the main active ingredients with pharmacological activities such as anti-aging, anti-tumor, anti-inflammatory, hypotensive, hypoglycemic, hypolipidemic, and immunomodulatory activities. Liquid fermentation of *G. lucidum* as a method for efficiently producing polysaccharide and triterpenoid yield of *A. cinnamomea* mycelium compared with conventional fermentation [148]. In the same study, ultrasound was also applied to a liquid culture of *A. cinnamomea* for 48 h, with an ultrasonic power of 60 W/L, frequency of 68 kHz, and a total treatment time of 15 min [148]. Under these ultrasound conditions and under autotrophic culture conditions, the mycelium yield was 7.78 g/L and the triterpene yield was 0.32 g/L, which were 17.52% and 39.13% higher, respectively, compared with the control group. Compared with conventional fermentation, ultrasound had a greater effect on the surface microstructure and internal cell structure of the *A. cinnamomea* mycelium [Fig. 4(b, c)], and there was no significant difference in the composition of triterpene compounds. Researchers have investigated the effects of different frequencies of ultrasonic treatment on the germination of *A. cinnamomea* spores. First, *A. cinnamomea* spores were inoculated into potato dextrose agar (PDA) medium, and then 8 h later, the spores were treated with ultrasound at frequencies of 22 kHz and 68 kHz for 15 min, and the fermentation continued for 19 h. Via microscopic observation, the researchers found that the germination rate of *A. cinnamomea* spores was increased by approximately 40–60%. Analysis using scanning electron microscopy revealed that ultrasound damaged the cell wall of *A. cinnamomea* spores to a certain extent. This was beneficial as it reduced the barrier of the cell wall to spore germination, thus promoting the germination of *A. cinnamomea* spores.

Several mechanisms have been proposed to explain the effects of physical fields in food fermentation applications. Low frequency ultrasound can influence the course of fermentation by improving mass transfer and cell permeability to improved process efficiency and production rates [4]. Magnetic fields have effects on foods at the subatomic particle level, or at the level of DNA, compounds, subcellular organelles and cells [83]. To understand the effects of physical fields on foods and to test the hypothesis, it is necessary to use multidisciplinary (physics, chemistry) and multi-technology (multi-omics, bioinformatics) to elucidate the interactions between food and physical fields.

Compared with traditional fermentation, low frequency ultrasound and low-intensity magnetic fields has been employed for enhancing fermentation rates. Physical field-assisted fermentation could improve the mass transfer, reduce fermentation periods, improve the productivity and quality of fermented products. Low frequency ultrasound processing of milk has been reported to reduce fermentation time of yoghurt and improve the final product properties [4], and low-intensity magnetic field-assisted fermentation can increase the mycelial biomass, polysaccharide and triterpenoid yield of *Antrodia cinnamomea* [110], and shorten fermentation time [121]. However, the use of ultrasound and magnetic fields in the food sciences field has not been sufficiently studied. Current research is mostly focused on assisting the extraction of active ingredients. One reason for this is that the mechanisms by which physical fields aid fermentation are unclear. A second reason is that ultrasound technology, despite more than 10 years of development, is often used as an auxiliary technology for research, not as a separate, cutting-edge technology.

Some investigators have also reported that physical field-assisted fermentation may also have negative effects on microorganisms in the content of volatile substances with antibacterial activity increased [147]. Wang [148] also found that the magnetic field had the strongest promotional effect on the growth and triterpene production of the *A. cinnamomea* mycelium at a magnetic field strength of 60 mT. At this field strength, the increase in the *A. cinnamomea* mycelium production was approximately 23.53% and in triterpene production was 28.19% at 36 h after the initiation of fermentation. After this time point, the mycelium and triterpene production showed a decreasing trend with the increase of magnetic field action time. The effects of magnetic field on the *A. cinnamomea* mycelium and triterpene production were consistent. The researcher also found that the surface morphology of the mycelium obtained by magnetic-field-assisted fermentation was loose and partly wrinkled (Fig. 4(d, e)), and the magnetic-field-assisted fermentation had no significant effect on the composition of triterpene compounds in the *A. cinnamomea* mycelium compared with conventional fermentation [148].
food fermentation. Ultrasound caused negative changes in wine sensory properties with the formation of negative oxidative smell of burns or smoke [4], while magnetic field had a negative effect on the number of Fusarium oxysporum conidia [149] and the production of extracellular C. militaris polysaccharides [37]. Using physical field for specific food fermentation applications, an appropriate frequency and power conditions should be considered.

Although ultrasound is widely used in hospitals, airports, and other places, the use of ultrasound for cleaning led to rapid developments in ultrasound technology with a consequent reduction in the cost of equipment, the interactions between ultrasound and microorganisms in food fermentation are complex and not well understood, which brought challenges to industrial application. As a mature technology, in addition to the need for continuous equipment innovations and for elucidating how to apply the technology well in the food field (for rare food and medicinal mushrooms), there is a need for in-depth research into the mechanisms underlying ultrasound action. The lack of application of magnetic fields in fermentation processes is partly due to the lack of understanding of the molecular conditions of most fermentation processes (especially those involving the synthesis of extracellular products). Conflicting results and lack of reproducibility are considered typical problems in magnetic field studies, and differences in researchers’ results may be due to the experimental design, microbial strain, exposure time, magnetic field system and field detection methods used.

5. Conclusions and prospects

There are many advantages associated with using low-frequency ultrasound and weak magnetic fields for assisting rare edible mushroom fermentation. Without a significant temperature rise, the cavitation, mechanical and chemical effects of ultrasound and the non-thermal biological effects of magnetic fields can be used to strengthen the biological mass transfer effect, promote reaction processes and modify biological macromolecules. These effects enhance biosynthesis efficiency and significantly improve product safety and biological activity. Thus, there are great prospects for the industrialization of these physical field technologies.

In previous research, physical fields have mostly been used for auxiliary strengthening and cannot be used independently to complete the processing operation. The use of the equipment by researchers across the globe in a single mode also limits the application of the physical fields in industry. Therefore, further basic theoretical research should be carried out to analyze the mechanisms by which physical fields act. In addition, industrial application problems associated with equipment development and industrial scale production should be addressed to overcome technical bottlenecks and to promote the industrialization process. Through these advancements, it should become possible to effectively use physical fields in the processing of food and agricultural products.

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CRediT authorship contribution statement

Wen Li: Conceptualization, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. Haile Ma: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision. Ronghai He: Conceptualization, Methodology, Supervision. Xiaofeng Ren: Conceptualization, Methodology, Supervision. Cunshan Zhou: Conceptualization, Methodology, Supervision.

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.

References

[1] A. Chávez-Martínez, R.A. Reyes-Villagran, A.L. Rentería-Montesrubio, R. Sánchez-Vega, J.M. Tirado-Gallegos, N.A. Bolivar-Jacobo, Low and high-intensity ultrasound in dairy products: applications and effects on physicochemical and microbiological quality, Foods 9 (2020) 1688.
[2] W.L. Fei-Fei, L. Chan, L.J. Hua-Qiang, L.Z. Zhao, X.J. Yong-Ping, Y.Z. Long, Q. Chen, Z.M. Zhang, Research progress of applications of ultrasonic technology in food industry, J. Food Saf. Qual. (2017).
[3] S.M.R. Azam, H. Ma, B. Xu, S. Devi, S.L. Stanley, M.A.B. Siddique, A.S. Mujumdar, J. Zhu, Multi-frequency multi-mode ultrasound treatment for removing pesticides from lettuce (Lactuca sativa L.) and effects on product quality, LWT, 143 (2021) 111147.
[4] K.S. Ojha, T.J. Mason, C.P. O’Donnell, J.P. Kerry, B.K. Tsivari, Ultrasound technology for food fermentation applications, Ultrason. Sonochem. 34 (2017) 410–417.
[5] R. Pathak, T. Leong, 1.29 - Consumer acceptability of ultrasonically processed foods, in: K. Knoerzer, K. Muthukumarappan (Eds.), Innovative Food Processing Technologies, Elsevier, Oxford, 2023, pp. 504–518.
[6] M. Ashokkumar, Applications of ultrasound in food and bioprocessing, Ultrason. Sonochem. 25 (2015) 17–23.
[7] A. Gallipoli, A. Giamico, M.G. Gagliano, C.M. Braguglia, Potential of high-frequency ultrasound to improve sludge anaerobic conversion and surfactants removal at different food/inoculum ratio, Bioresour. Technol. 159 (2014) 207–214.
[8] M. Matouq, Z. Al-Asber, N. Susumu, T. Tagawa, H. Karapangioti, The kinetic of dyes degradation resulted from food industry in wastewater using high frequency of ultrasound, Sep. Purif. Technol. 135 (2014) 42–47.
[9] H. Wang, K. Xu, Y. Ma, Y. Liang, H. Zhang, L. Chen, Impact of ultrasoundication on the aggregation structure and physicochemical characteristics of sweet potato starch, Ultrason. Sonochem. 63 (2020), 104868.
[10] Y. H Emmar, C. Xu, S. Wu, M. Ashokkumar, Size reduction of “reformed casein micelles” by high-power ultrasound and high hydrostatic pressure, Ultrason. Sonochem. 63 (2020), 104929.
[11] H. Zhang, G. Chen, M. Liu, X. Mei, Q. Yu, J. Kan, Effects of multi-frequency ultrasound on physicochemical properties, structural characteristics of gluten protein and the quality of noodle, Ultrason. Sonochem. 67 (2020), 105135.
[12] J. Liu, H. Ma, B. Wang, A.-E.G.-A. Yagoub, K. Wang, R. He, C. Zhou, Effects and mechanism of dual-frequency power ultrasound on the molecular weight distribution of corn gluten meal hydrolysates, Ultrason. Sonochem. 30 (2016) 48–51.
[13] H. Heidari, S. Ghanbari-Rad, E. Hashbi, Optimization deep eutectic solvent-based ultrasound-assisted liquid-liquid microextraction by using the desirability function approach for extraction and preconcentration of organophosphorus pesticides from fruit juice samples, J. Food Compos. Anal. 87 (2020), 103389.
[14] E. Bruno Romanini, L. Misturini Rodrigues, A. Finger, T. Perez Cantauia Chieritto, M. Regina da Silva Scapim, G. Scaramal Madrona, Ultrasound assisted extraction of bioactive compounds from BRS Violet grape pomace followed by alginate-Ca2+ encapsulation, Food Chem. 338 (2021), 128101.
[15] S.K. Ulg, F. Jihadidile, J. Wu, Novel technologies for the production of bioactive peptides, Trends Food Sci. Technol. 108 (2021) 27–39.
[16] S. Shokri, S.S. Shekarforoush, S. Hosseinizadeh, Stimulatory effects of low intensity ultrasound on the growth kinetics and metabolic activity of Lactoccus lactis subsp. Lactis, Process Biochemistry 86 (2020) 1–8.
[17] Z. Zhu, P. Zhang, D.-W. Sun, Effects of multi-frequency ultrasound on freezing rates and quality attributes of potatoes, Ultrason. Sonochem. 60 (2020), 104733.
[18] Y.-Y. Wang, M. Tayyab Rashid, J.-K. Yan, H. Ma, Effect of multi-frequency ultrasound thawing on the structure and rheological properties of myoglobin proteins from small yellow croaker, Ultrason. Sonochem. 70 (2021), 105552.
[19] Y. Li, X. Wang, Z. Wu, N. Wang, M. Yang, Dehydration of hawthorn fruit juices using ultrasound-assisted vacuum drying, Ultrason. Sonochem. 68 (2020), 106241.
[20] X. Fan, S. Li, A. Zhang, H. Chang, X. Zhao, Y. Lin, Z. Feng, Mechanism of change of the physicochemical characteristics, gelation process, water state, and microstructure of okara tofu analogues induced by high-intensity ultrasound treatment, Food Hydrocolloids 111 (2021), 106241.
[21] O. Sarheed, D. Shouqair, K.V.R.N.S. Ramesh, T. Khaleel, M. Amin, J. Boateng, M. Drechler, Formation of stable nanoemulsions by ultrasound-assisted two-step emulsification process for topical drug delivery: Effect of oil phase composition and surfactant concentration and loratadine as ripening inhibitor, Int. J. Pharm. 576 (2020), 118952.
[22] E.A. Alenyorege, H. Ma, I. Ayim, J.H. Abeto, C. Hong, C. Zhou, Effect of multi-frequency multi-mode ultrasound washing treatments on physicochemical, antimicrobial activity and microbial quality of tomato, J. Food Meas. Charact. 13 (2019) 677–686.

[23] G. Cavotto, A. Binello, I. Low-frequency, high-power ultrasound-assisted food component extraction, in: K. Koserer, P. Juliano, G. Smithers (Eds.), Innovative Food Processing Technologies: Their possible origin, pp. 187–198, 2015.

[24] A. Taise Mustapha, C. Zhou, H. Wahia, R. Amanor-Atimoh, P. Ou, A. Qudus, O. Abiola Falakoye, H. Ma, Sonozonation, Enhancing the antimicrobial efficiency of aqueous ozone washing techniques on cherry tomato, Ultrasound. Sonom. 64 (2020) 105059.

[25] N. Barman, L.S. Badwaik, Effect of ultrasound and centrifugal force on carambola (Averrhoa carambola L.) slices during osmotic dehydration, Ultrasound. Sonom. 34 (2018) 37–44.

[26] X. Gao, T. Feng, E. Liu, P. Shan, Z. Zhang, L. Liao, H. Ma, Ougan juice debittering using ultrasound-aided enzymatic hydrolysis: Impacts on aroma and taste, Food Chem. 345 (2021), 128707.

[27] L. Sun, L. Liu, L. Yang, W. Mabbour, B.K. Mintah, R. He, H. Ma, Effects of low-intensity ultrasound on the biomass and metabolite of Ganoderma lucidum in liquid fermentation, J. Food Process. Eng. 44 (2021), e13601.

[28] H. Zhang, H. Ma, W. Liu, J. Pei, Z. Wang, H. Zhou, Y. Yan, Ultrasound enhanced production and antioxidant activity of polyphenolics from mycelial fermentation of Phellinus igniarius, Carbohydr. Polym. 113 (2014) 380–387.

[29] H. Yu, Q. Zhong, Y. Liu, Y. Guo, Y. Xie, W. Zhou, Y. Yao, Recent advances of ultrasound-assisted Maillard reaction, Ultrasound. Sonom. 64 (2020), 104844.

[30] X. Zhu, Z. Zhang, L.M. Hinds, D.W. Sun, B.K. Tiwari, Applications of ultrasound to enhance fluidized bed drying of Ascorbyl palmitate: Drying kinetics and product quality assessment, Ultrasound. Sonom. 70 (2021) 102598.

[31] A.R. Jumbrak, M. Simunek, M. Petrovic, H. Bedic, Z. Herceg, H. Juretic, Aromatic profile and sensory characterization of pulsed sonicated cranberry juice and nectar, Ultrasound. Sonom. 38 (2017) 783–793.

[32] C. Wu, D.J. McClements, M. He, L. Zheng, T. FENG, Y. Li, Preparation and characterization of okra nanocellulose fabricated using sonicication or high-pressure homogenization treatments, Carbohydr. Polym. 255 (2022) 117694.

[33] Q. Liang, X. Ren, X. Zhang, T. Hou, M. Chalamaiah, H. Ma, B. Xu, Effect of low-intensity magnetic field on the gel properties of pork myofibrillar proteins, Meat Sci. 160 (2020) 104587.

[34] T. Kobayashi, T. Kobayashi, Y. Hosaka, N. Fujii, Ultrasound-enhanced membrane-cleaning processes applied water treatments: influence of sonic frequency on filtration treatments, Ultrasonics 41 (2003) 185–190.

[35] M.O. Lamminen, H.W. Walker, L.K. Weavers, Mechanisms and factors influencing the ultrasonic cleaning of particle-foiled ceramic membranes, J. Membr. Sci. 237 (2004) 213–223.

[36] Z. Zhang, F. Xiong, Y. Wang, C. Dai, X. Mabbour, B. Mintah, R. He, H. Ma, Fermentation of Phellinus igniarius, Carbohydr. Polym. 113 (2014) 380–387.

[37] M. Taskin, N. Esim, M. Genisel, S. Ortucu, I. Hasenekoglu, O. Canli, S. Erdal, Z. Zhang, F. Xiong, Y. Wang, C. Dai, Z. Xing, M. Dabbour, B. Mintah, R. He, H. Ma, Ultrasound-enhanced membrane cleaning processes applied water treatments: influence of sonic frequency on filtration treatments, Ultrasonics 41 (2003) 185–190.

[38] H.C. Deeth, N. Datta, Heat treatment of milk | non-thermal technologies: pulsed electric field technology and ultrasonication, in: J.W. Fuquay (Ed.), Encyclopedia of Dairy Sciences (Second Edition), Academic Press, San Diego, 2011, pp. 738–743.

[39] M. Zhang, Q. J, Study on increasing neutral protease production by pulsed electric field and ultrasound processing, J. Food Eng. 95 (2010) 137–145.

[40] J.H. Mok, W. Choi, S.H. Park, S.H. Lee, S. Jun, Emerging pulsed electric field (PEF) and static magnetic field (SMF) combination technology for food freezing, Int. J. Refrig. 50 (2015) 137–145.

[41] S. Guo, X.J. Wang, G.Z. Wang, Application of magnetic field to fruit and vegetable preservation, Food Res. Dev. (2015).

[42] H.F. Zhang, L.Q. Zhao, Huibin, Application of heat treatment on storage and preservation of fruit and vegetables, storage and preservation, (2005).

[43] J.R. Mattar, M.F. Turk, M. Nomis, N.L. Lebovka, H. El Zakhem, E. Vorobiev, Alternating electric field technology and ultrasonication, in: J.W. Fuquay (Ed.), Encyclopedia of Dairy Sciences (Second Edition), Academic Press, San Diego, 2011, pp. 738–743.

[44] S. Guo, P. Lv, Y. Cai, C. Tu, X. Ma, P. Ning, Enhanced anaerobic fermentation of dairy manure by microelectrolysis in electric and magnetic fields, Renewable Energy 146 (2020) 2758–2765.

[45] A. Wasak, R. Drozd, D. Jankowski, R. Rakociy, The influence of rotating magnetic field on bio-catalytic dye degradation using the horseradish peroxidase, Biochem. Eng. J. 147 (2019) 481–87.

[46] Y. Zhou, Z. Zhang, S.G. Zhang, Y. Bi, P. Zhang, C. Fang, W. Hu, Z.B. Liu, L. Zhou, Using orthogonal array design to optimize the extraction of walferry flavonoids by magnetic field treatment, Food Sci. 33 (2012) 98–101.

[47] J. Zhang, W.U. Song-Hai, W.X. Chen, F. Wang, Effects of static magnetic field on antimicrobial activities of microorganisms, J. Photochem. Photobiol. B 58 (2001) 9–14.

[48] M.Q. Zhou, G. Yu, Study on extraction from orange peel under normal magnetic field strength, J. Food Sci. 33 (2012) 98–101.

[49] M. Gifra, J.Z. Fields, A. Farhadi, Electromagnetic cellular interactions, Prog. Biophys. Mol. Biol. 105 (2010) 223–246.

[50] R.J. Zhou, M.A. Hai-Li, W.L. Fang, H.N. Zhang, Progress in understanding magnetic biological effect in food processing, Food Science (2014).

[51] S.J. Webb, A.D. Booth, Absorption of microwaves by microorganisms, Nature.

[52] C.F. Blackman, L.S. Kinney, D.E.W. House, Multiple power-density waves and magnetic field effects on microorganisms, Electromagnetics 10 (1990) 115–128.

[53] Z. Zhang, G. Bai, D. Xu, Y. Gao, Effects of ultrasound on the kinetics and thermodynamics properties of papain entrapped in modified gelatin, Food Hydrocolloids 105 (2020), 105757.

[54] H. Yacoob, Amending the efficiency of antimicrobial against multi-drug-resistant Pseudomonas aeruginosa by low-frequency magnetic fields, Bull. Exp. Biol. Med. 170 (2020).

[55] H. Li, G. Li, L. Gao, L. Yin, Y. Zhang, Effect of priming low-frequency magnetic fields on zero-Mg2+ – induced epimelisepid discharge in rat hippocampal slices, Epilepsy Res. 167 (2020), 106644.

[56] A. Maldonado-Moreles, T. Cordova-Fraga, H. Bonilla-Jaime, P.Y. Lopez-Camacho, V. Jalili, Magnetic field-assisted solid-phase extraction of nucleoside drugs using Fe3 O4 @PANI core/shell nanocomposite, J. Liq. Chromatogr. Relat. Technol. 43 (2020) 92–105.

[57] J.H. Fernandez, O. Abiola Fakayode, H. Ma, Sonozonation, Enhancing the antimicrobial efficiency of...
J.Q. Jia, H.L. Ma, W.R. Zhao, Z.B. Wang, L. Luo, Effect of ultrasound treatment on the interaction of brine with pork meat, Ultrason. Sonochem. 76 (2021) 105613.

S.J. Zhu, Y.H. Shi, I.E. Guo-Wei, Effects of ultrasound on the hydrolysis of casein by trypsin, J. Wiley Univ. Light Ind. (2005).

Y. Zou, Y. Ding, W. Feng, W. Qiu, Y. Chen, H. Wu, W. Xiang, L. Yang, Enzyme kinetics, thermodynamics and model of porcine cerebral protein with single-frequency ultrasonic and pulsed ultrasound-assisted processing, Ultrason. Sonochem. 28 (2016) 294–301.

D.J. McClements, Choudhury, in: A.G. Gaonkar (Ed.), Food Processing, Elsevier Science B.V., Amsterdam, 1995, pp. 59–70.

S. Ruan, J. Luo, Y. Li, Y. Wang, S. Huang, F. Lu, H. Ma, Ultrasound-assisted liquid-state fermentation of soybean meal with Bacillus subtilis: Effects on peptide content, ACE inhibitory activity and biomass, Process Biochem. 91 (2020) 73–82.

W.G. Pitt, S.A. Ross, Ultrasound increases the rate of bacterial cell growth, Biotechnol. Prog. 19 (2003) 1038–1044.

M.A.M. Absenghe, N. D’Souza, J. Vidacchichi, S. Frakanch, K. Silva, A. Karim, Effects of ultrasound on the ultrasonic profile of fermented milk products incorporated with lactic acid bacteria, Int. Dairy J. 90 (2019) 1–14.

G. Huang, Y. Tang, L. Sun, X. Hing, M. Ha, Ultrasound irradiation of low intensity with a mode of sweeping frequency enhances the membrane permeability and cell growth rate of Candida tropicalis, Ultrason. Sonochem. 37 (2017) 518–528.

Y. Zhou, Z. Zhang, S.-G. Zhang, Y. Bi, P. Zhang, C. Pang, W. Hu, Z.-B. Liu, L. Zhou, X. Xiao, Using orthogonal array design to optimize the extraction of woolberry flavonoids by magnetic field treatment, Food Science 33 (2012) 98–101.

F. Cristina, Fraga, Alexandra, Valério, V. Almeida, D. Oliveira, Marco, L. Di, Debora, Effect of magnetic field on the Eversa? Transform 2.0 enzyme: Enzymatic activity and structural conformation, Int. J. Biol. Macromol. (2018).

N. Emamdadi, M. Gholizadeh, M.R. Houindokht, Investigation of static magnetic field effect on horseradish peroxidase enzyme activity and stability in enzymatic oxidation process, Int. J. Biol. Macromol. 170 (2021) 189–195.

Study on increasing说话能力 by the use of ultrasound, Ultrasonics 59 (2017) 302–308.

X. Wang, X. Wu, J. Li, A. Wang, G. Li, X. Ren, W. Yin, Ultrasound-assisted deep eutectic solvent extraction of echinocidin and oleuropein from Syringa pubescens Turcz, Ind. Crops Prod. 151 (2020), 112442.

L. Yang, J. Cai, D. Li, X. Wu, L. Li, Y. Liu, M. Tang, Y. Chen, Y. Zhang, X. Xiao, Using ultrasound to improve the development of Lactobacillus sake, Food Sci. Procedia 9 (2016) 317–321.

H. Wang, T. Yao, Y. Li, S. Wu, D. Li, Y. Liu, H. Manickam, P.L. Show, Application of ultrasonication at different microbial growth stages during apple juice fermentation by Lactobacillus plantarum: Investigation on the metabolic response, Ultrason. Sonochem. 73 (2021) 105486, https://doi.org/10.1016/j.ultsonch.2021.105486.

R. Xie, L. Jiang, Y. Liu, J. Wang, X. Li, Y. Yang, J. Wei, Y. Zhang, Y. Li, Q. Li, Y. Zhang, X. Tang, X. Wang, L. Hu, Q. Wang, J. Han, H. Wang, Y. Li, J. Cao, Y. Gao, H. Huang, J. Zhao, X. Qin, Y. Li, P. Song, A. Wang, L. Ma, Y. Wang, Y. Han, Y. Liu, X. Lu, S. Liu, J. Zhang, X. Xiao, Magnetic field effects on the antioxidant activity of Monascus purpureus in response to low frequency magnetic field, Food Res. Dev. (2018) 1–13.

X. Wang, X. Wu, J. Li, A. Wang, G. Li, X. Ren, W. Yin, Ultrasound-assisted deep eutectic solvent extraction of echinocidin and oleuropein from Syringa pubescens Turcz, Ind. Crops Prod. 151 (2020), 112442.

M. S. Zhou, L. I. Ying-Ying, L. U. Zhi-Fang, Effects of ultrasonic infiltration on the growth of S. cerevisiae and low ultrasonic on the concentration of Ca2+, Biophys. J. 96 (12) (2009) 4866–4876.

Y. Zou, Y. Ding, W. Feng, W. Qiu, Y. Chen, H. Wu, W. Xiang, L. Yang, Enzyme kinetics, thermodynamics and model of porcine cerebral protein with single-frequency ultrasonic and pulsed ultrasound-assisted processing, Ultrason. Sonochem. 28 (2016) 294–301.

D.J. McClements, Choudhury, in: A.G. Gaonkar (Ed.), Food Processing, Elsevier Science B.V., Amsterdam, 1995, pp. 59–70.

S. Ruan, J. Luo, Y. Li, Y. Wang, S. Huang, F. Lu, H. Ma, Ultrasound-assisted liquid-state fermentation of soybean meal with Bacillus subtilis: Effects on peptide content, ACE inhibitory activity and biomass, Process Biochem. 91 (2020) 73–82.

W.G. Pitt, S.A. Ross, Ultrasound increases the rate of bacterial cell growth, Biotechnol. Prog. 19 (2003) 1038–1044.
[139] S.F. Barnes, Mechanisms for electric and magnetic fields effects on biological cells, IEEE Trans. Magn. 41 (2005) 4219–4224.

[140] I.O. Santos, K.M. Deamici, J. Garda-Buffon, V. Costa, J. Alberto, B.C. Menestrino, Magnetic treatment of microalgae for enhanced product formation, World J. Microbiol. Biotechnol. (2017).

[141] G.N. Lucena, C.C.d. Santos, G.C. Pinto, R.D. Piazza, W.N. Guedes, M. Jafelici Júnior, A.V. de Paula, R.P.C. Marques, Synthesis and characterization of magnetic cross-linked enzyme aggregate and its evaluation of the alternating magnetic field (AMF) effects in the catalytic activity, J. Magn. Magn. Mater. 516 (2020), 167326.

[142] M. Gao, F. Xia, P. Zhu, Influence of alternating magnetic field on growth and polysaccharide outside the cell of lions mane hericium, Trans. Chin. Soc. Agric. Mach. 40 (2009) 139–340.

[143] Z. Wei, Response regularity of Phellinus igniarius based on submerged fermentation assisted by weak magnetic field, Master Thesis, Jiangsu University, Jiangsu Province, China., (2017).

[144] H.Y. Zhang, Effects of magnetic treatment on exopolysaccharide of Cordyceps militaris, J. Anhui Agric. Sci. (2010).

[145] X.U. Ti-Sen, The effects of magnetic treatment on the growth amount of cordyceps militaris, J. Dezhou Univ., (2011).

[146] L. Zhu, H. Ma, M. Lu, P. Wu, Effects of low-intensity alternating magnetic field on liquid fermentation of Antrodia camphorata, Mod. Food Technol., 035 (2019) 153-159,154.

[147] Z. Gan, H. Jie, C. Chang, X. Wang, D. Pan, Study of the effect of weak magnetic field on the decolorization of azo dye by Fe-based amorphous alloy powders, Gongneng Cailiao/J. Funct. Mater. 46 (2015), 14140-14143 and 14148.

[148] W. Wang, Research on effect of ultrasound and magnetic field on fermentation of Antrodia cinnamomea ATCC 200183, Master Thesis, Jiangsu University, Jiangsu Province, China, 2015.

[149] P. Nagy, G. Fischl, Effect of static magnetic field on growth and sporulation of some plant pathogenic fungi, Bioelectromagnetics 25 (2010) 316–318.