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# Ultrasound-assisted extraction and modification of dietary fiber

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**Abstract:** Dietary fiber has good nutritional value and physiological function. Therefore, how to prepare high-quality dietary fiber has become a hot issue in the field of dietary fiber research. Herein, the research status of extraction and modification of dietary fiber by ultrasonic technology in recent years was summarized. The characteristics and working principle of ultrasonic were analyzed. The effect of ultrasonic extraction and modification was analyzed, and the working mechanism and influencing factors of ultrasonic extraction and modification were expounded. Finally, the existing problems were summarized and the development prospect of ultrasonic technology was prospected, in order to provide theoretical reference for high-value utilization of dietary fiber resources. It indicates that the ultrasonic technology has the advantages of high extraction efficiency, mild extraction conditions, excellent modification effect, environmental friendliness and low energy consumption, which makes it one of the most promising technologies in the extraction and modification of dietary fiber.

**Keywords:** Ultrasound-assisted extraction, modification, affecting factors, dietary fiber

## 1. Introduction

Dietary fiber is known as "the seventh nutrient" [1]. Dietary fiber has many beneficial effects in human body, including improving intestinal flora, preventing intestinal



diseases, lowering blood cholesterol, improving glucose tolerance, reducing blood glucose response, preventing cardiovascular diseases, and promoting growth and development [2-3]. According to the solubility difference in water, dietary fiber is mainly divided into soluble dietary fiber (SDF) and insoluble dietary fiber (IDF). SDF mainly includes pectin and part of hemicellulose, while IDF mainly includes cellulose and lignin. Dietary fiber comes from a wide range of sources, mainly from plant cell walls. Grains, beans, fruits and vegetables can all be used as raw materials for extracting dietary fiber [4]. Studies have shown that there is often a high content of IDF [5] in the by-products of food processing, such as peel, pomace, bran and bean dregs. However, due to the poor water solubility and rough taste of this kind of dietary fiber, it is difficult to effectively utilize IDF in these by-products. At the same time, in the natural plant cell wall, cellulose is the skeleton of the cell wall structure, and hemicellulose and lignin are dispersed in the fiber, which makes it difficult to extract dietary fiber fully [6]. Therefore, it is a hot issue in the field of dietary fiber research to find suitable extraction and modification methods to improve the utilization rate and functional characteristics of dietary fiber.

Among many methods for extracting and modifying dietary fiber, ultrasonic technology has the advantages of high extraction efficiency, mild extraction conditions, excellent modification effect, environmental friendliness and low energy consumption, which makes it one of the most promising technologies for extracting and modifying dietary fiber [7]. Ultrasound can destroy the plant cell wall and make dietary fiber well dispersed in the solvent. It can also transform some water-insoluble



components into water-soluble components, making the dense spatial network structure loose. In addition, the cavitation effect and mechanical effect of ultrasound enable it to extract and modify dietary fiber at room temperature, shorten the extraction time and improve the extraction efficiency, and greatly reduce the energy consumption [8]. Therefore, the characteristics and working principle of ultrasonic technology were analyzed, the research status of ultrasonic technology in extracting and modifying dietary fiber in recent years was summarized, and the mechanism and influencing factors of ultrasonic technology in extracting and modifying dietary fiber were discussed in order to provide useful reference for the application of ultrasonic technology in the development of dietary fiber resources. At the same time, the development trend of dietary fiber modification technology in the future is prospected, which provides theoretical basis and practical guidance for further research and application of dietary fiber modification technology.

## 2. Overview of ultrasonic technology

Ultrasonic wave is an inaudible sound wave with a frequency higher than 20 kHz. Like other sound waves, it is generated by periodic vibration of particles in a medium under the action of mechanical force and can only propagate in the medium. In the food industry, ultrasound can be divided into high-frequency low-intensity diagnostic ultrasound (5 ~ 10 MHz, intensity < 1 w/cm<sup>2</sup>) and low-frequency high-intensity power ultrasound [9] (20 ~ 100 kHz, intensity 1 ~ 1 000 w/cm<sup>2</sup>) according to different frequencies. The former is mainly used for nondestructive testing of food materials



during processing and storage to ensure that the quality and safety of materials meet the standards. For example, it can be used to determine the physical and chemical characteristics of food such as crispness [10], hardness [11] and oil content [12]; The latter can produce fast-moving micro-bubble flow, and the bursting of bubbles leads to physical, chemical and even biochemical changes in food, which can be used for most food processing and preservation, such as auxiliary freezing, changing fat texture characteristics, protein emulsification, defoaming, sterilization, extraction of bioactive substances and modification of food ingredients [13-15].

When the ultrasonic wave propagates in the medium, the medium changes due to the interaction between the ultrasonic wave and the medium, resulting in a series of mechanical and electromagnetic ultrasonic effects, mainly including mechanical response and cavitation effect [16]. The mechanical effect of ultrasonic wave means that the propagation of ultrasonic wave in medium can make medium particles vibrate in its propagation space, thus strengthening the diffusion and propagation of medium. In addition, easily broken bubbles [17] will be formed in water by ultrasonic treatment. These bubbles are in an unstable state and will undergo the process of generation, development and rapid closure. When they are quickly closed and broken, they will produce a micro-shock wave, which will make local areas have great pressure. The phenomenon that bubbles form in liquid and then close quickly is the cavitation effect.

The working mechanism of ultrasonic extraction and modification of dietary fiber is mainly related to cavitation effect. During the extraction and modification of dietary



fiber, sound waves will propagate in a container filled with medium, resulting in compressed phase and sparse phase. In the case of insufficient sound pressure, cavitation bubbles will increase and contract in sparse cycle and compression cycle respectively. If the bubble can't reach the critical size of collapse or inward rupture, this phenomenon is called stable cavitation, which weakens the cavitation effect. When the pressure is large enough, the bubble will expand rapidly, and when the bubble exceeds its critical size, it will collapse or burst inward, which is called instantaneous cavitation. At this time, a lot of energy will be released, which will increase the temperature and pressure instantly, and at the same time form high shear force and turbulence [18], thus destroying the plant cell wall, releasing dietary fiber into the solvent, achieving the purpose of extracting dietary fiber, and also allowing water molecules to release free radicals and react with dietary fiber molecules for modification (Fig. 1).

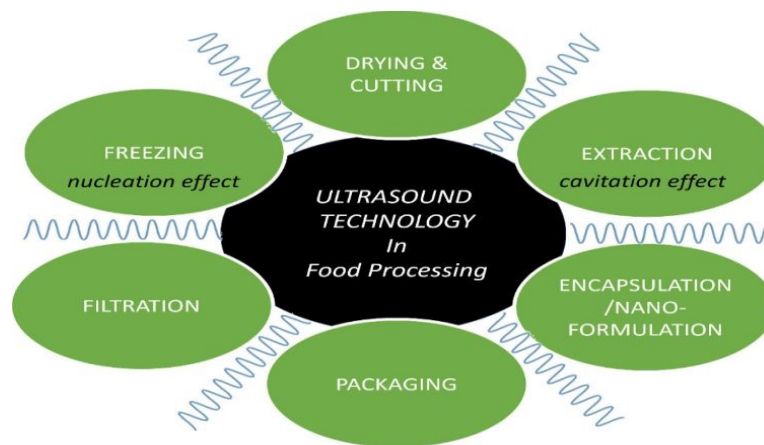


Fig. 1. The ultrasound technology for food processing.

### 3. Ultrasonic extraction of dietary fiber



Dietary fiber, as a kind of plant active polysaccharide, can be effectively extracted under the effect of ultrasonic cavitation. Compared with other extraction methods, the conditions of ultrasonic extraction are milder. Because the rupture and oscillation of cavitation bubbles can cause crushing, erosion, acoustic hole effect, capillary effect, shear force and turbulence, etc. [19], mass transfer is enhanced, so ultrasonic extraction can be carried out at a lower temperature, with less solvent and in a shorter time, which can improve the yield and reduce the energy consumption. Cavitation effect can not only break the cell wall, but also destroy the molecular structure of the extracted substance [20]. Therefore, when using ultrasonic to extract dietary fiber, it is necessary to control the ultrasonic parameters, extraction time, extraction solvent, dosage and concentration of solvent, etc. In the process of ultrasonic extraction of dietary fiber, there are two ways: single extraction and auxiliary extraction. The following two ways are described and compared respectively.

### 3.1 Ultrasonic extraction alone

Ultrasonic wave is an economical, environmentally friendly and simple extraction method. KUREK et al. [21] showed that the yield of ultrasonic extraction was higher than that of enzymatic extraction when extracting millet dietary fiber, and the grain diameter of millet dietary fiber was larger and denser. WEN et al. [22] extracted SDF from coffee silver skin under the condition of ultrasonic wave power of 200 W and treatment for 20 min, and the yield reached (22.8 ± 0.3)%, and the extraction time was significantly shorter than that of hot water extraction. Ultrasonic extraction of dietary fiber can effectively improve the yield, and the extracted dietary fiber has better water



holding capacity, oil holding capacity, swelling capacity and cation exchange capacity, and has a more complex and porous structure [23-27].

### 3.2 Ultrasonic-assisted extraction

In research and practical application, ultrasonic-assisted extraction is more widely used than single extraction. This is because the yield of auxiliary extraction is high, the extraction time is short, and the chemical composition and structure are not easily destroyed. Ultrasonic-assisted alkaline method, ultrasonic-assisted enzymatic method and ultrasonic-assisted microwave method are several commonly used methods. Liu [28] extracted IDF from mung bean skin under the conditions of alkali concentration of 3.0 mol/L, liquid-material ratio of 15 : 1 ( mL : g), temperature of 52 °C, ultrasonic power of 350 W and extraction time of 148 min, and the maximum yield was (66.28%). MOCZKOWSKA et al. [29] treated flaxseed with ultrasound at 55 °C for 15 min, and then treated with enzyme, and the highest SDF yield was (68.90%). Chen et al [30] extracted SDF from taro peel under the conditions of ultrasonic power of 327 W, microwave power of 40 W, liquid-material ratio of 38 : 1 ( mL : g) and extraction time of 12 min, and the highest yield was (18.58%). The yield of dietary fiber extracted by ultrasonic wave is generally higher than that by ultrasonic wave alone. In terms of functional characteristics, compared with single extraction, the extracted dietary fiber has a more complex and porous structure; It also improves cholesterol binding ability and glucose adsorption ability, and has good hypoglycemic ability and thermal stability. This is because when combined with other



methods, ultrasound can accelerate the rupture of plant cell walls, so that dietary fiber in cells can be released, diffused and dissolved faster, thus shortening the time and improving the yield [31-35] (Table 1).

**Table 1.** Application of ultrasound-assisted extraction of dietary fiber.

Way	Raw material	Extraction effect	References
Ultrasonic-assisted alkaline method	Microcystis marine	Under the optimal conditions, the yield of U-SDF is (17.50 ± 0.26)%, which is increased by 150.72%.	[31]
	Papaya peel	The yield of SDF is 36.99%, and the main sugar is pectin sugar, which has less crystallization and higher thermal stability, water holding capacity, oil holding capacity and swelling capacity.	[32]
Ultrasonic-assisted enzymatic method	Seedless Rosa roxburghii residue	The highest ratio of SDF /IDF in Rosa roxburghii residue is 0.638 ± 0.012. The swelling power and water-holding capacity of total dietary fiber in Rosa roxburghii residue are 2.761 mL/g and 3.248 g/g, respectively. The oil-holding capacity is 2.603 g/g, and the solubility is 37.643%.	[33]
	bamboo shoots	The yields of SDF and IDF were (12.29 ± 0.12)% and (55.98 ± 2.57)%, respectively, and the particle size decreased, showing a porous and loose structure, with good hypoglycemic activity.	[34]
Ultrasonic-assisted microwave method	Black bean skin	The SDF yield can reach (19.12 ± 0.23)%, the swelling power is 585.71%, the water holding capacity is 11.89 g/g, and the oil holding capacity is 10.52 g/g.	[35]

g/g: It indicates how many grams of oil can be adsorbed or retained per gram of material.

mL/g: It represents the volume (milliliter) occupied by each gram of dry matter after fully absorbing water, and is used to measure the swelling capacity of materials after meeting water.



#### 4. Ultrasonic treatment of modified dietary fiber

Ultrasonic treatment can degrade high polymers such as dietary fiber and modify them. The modified dietary fiber usually has better water holding capacity, oil holding capacity and swelling capacity, smaller particle size and larger specific surface area. Ultrasonic modification can reduce the treatment temperature, shorten the time and optimize the modification effect, and can modify dietary fiber alone or with other technologies.

##### 4.1 Ultrasonic modification alone

Ultrasonic modification is a low energy consumption, pollution-free and relatively safe technology, but the modification effect is relatively simple. Its working mechanism has two aspects: on the one hand, the collapse of cavitation bubbles accelerates the friction between solvent molecules and polymer molecules, thus causing mechanical degradation of C-C bond breakage; On the other hand, chemical degradation caused by chemical reaction between polymer molecules and high-energy molecules. CHEN et al. [36] studied the effects of different ultrasonic frequencies on the physical and chemical properties of modified citrus pectin. The results showed that the molecular weight and viscosity of modified pectin were lower than those of the control group. After ultrasonic modification, the glucose and cholesterol adsorption capacity of dietary fiber were obviously improved, and the viscosity was also increased, and the thermal stability was improved. A certain amount of IDF is converted into SDF, and the solubility is enhanced. Zhang et al. [37] modified the dietary fiber of *Phyllostachys praecox* at ultrasonic power of 100 W, frequency of 25



kHz, liquid-material ratio of 10 : 1, and room temperature for 1 h. After modification, the physical and chemical properties and antioxidant activity of the dietary fiber of *Phyllostachys praecox* were significantly improved, and at the same time, the chemical bond was broken and the molecular rearrangement was caused, resulting in some changes in the dietary fiber composition of *Phyllostachys praecox*. Niu et al. [38] showed that the water holding capacity, swelling capacity and oil holding capacity of oat dietary fiber modified by ultrasonic treatment were significantly improved, the particle size was reduced, the surface structure was loose, and honeycomb-like porous characteristics appeared. Ultrasonic modification can improve the swelling capacity, water holding capacity and oil holding capacity of dietary fiber, which shows better functions and physical and chemical properties than unmodified dietary fiber [39-43].

#### 4.2 Ultrasonic-assisted modification

Ultrasonic-assisted modification has shorter time, higher efficiency and wider application. Huang et al. [44] showed that the water-holding capacity, oil-holding capacity and swelling power of garlic straw dietary fiber were significantly improved by ultrasonic-assisted enzymatic treatment, and the microstructure was looser and the adsorption was stronger, which was better than the traditional single enzymatic method and water bath method. Compared with the dietary fiber modified by other methods alone, the dietary fiber modified by ultrasonic wave has higher water holding capacity and oil holding capacity, and the functional properties such as cholesterol adsorption capacity and glucose adsorption capacity of the modified dietary fiber have



also been improved, which shows that ultrasonic wave can not only effectively modify dietary fiber, but also cooperate with other modification methods to further improve the modification effect of dietary fiber [45-49] (Table 2).

**Table 2.** Application of ultrasound-assisted modification of dietary fiber.

Way	Raw material	Modification effect	References
Ultrasonic-assisted microwave technology	Black bean skin	The water holding capacity, water swelling capacity and oil holding capacity are 3.79 g/g, 1.39 ml/g and 1.14 g/g, respectively, which are 9.54%, 23.01% and 17.53% higher than the original SDF. The cholesterol binding capacity was 13.8 mg /g.	[45]
	pomelo peel	It shows the highest water holding capacity, oil holding capacity, cholesterol adsorption capacity, glucose adsorption capacity and nitrite ion adsorption capacity.	[46]
Ultrasonic-assisted enzymatic method	Rose pomace	Ultrasonic pretreatment is helpful to improve water holding capacity, oil holding capacity, cation exchange and cholesterol adsorption capacity, but it will reduce glucose adsorption capacity.	[47]
	Sisal waste and Moringa stems	The ratio of IDF and SDF is reduced, and the particle size is reduced; The water-holding capacity, expansion capacity and oil-holding capacity are all improved.	[48]
Ultrasonic-assisted acid method	Sweet potato residue	The dispersion index is the smallest, the system is the most uniform, and the oil holding capacity and water holding capacity are the best.	[49]

g/g: It indicates how many grams of oil can be adsorbed or retained per gram of material.

mL/g: It represents the volume (milliliter) occupied by each gram of dry matter after fully absorbing water, and is used to measure the swelling capacity of materials



after meeting water.

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## 5. Factors affecting ultrasonic extraction and modification of dietary fiber

When using ultrasonic wave to extract and modify dietary fiber, the frequency, power and intensity of ultrasonic wave will have an impact on the final effect; At the same time, environmental factors such as treatment temperature, raw material characteristics and medium conditions will also have an impact.

### 5.1 Power and frequency

The power of ultrasonic wave is also called amplitude percentage, ranging from 0 to 100%, where 100% amplitude represents the rated power of the equipment. Studies have shown that the yield and modification effect of dietary fiber from *Microcystis* marine increase with the increase of ultrasonic power, and then decrease after reaching the peak [31]. This may be because with the increase of power, the influence of cavitation bubble rupture is enhanced, which leads to the tissue fragmentation and pore formation of marine *Microcystis*, and after reaching the peak, it turns into an adverse effect on dietary fiber.

There is little research on the extraction and modification of dietary fiber by ultrasound at different frequencies, and most of the research focuses on the constant frequency. Bagherian et al. [25] extracted dietary fiber from wheat bran, Hu et al. [41] modified the dietary fiber of sunflower meal by ultrasonic wave, and YANG et al. [48] modified the dietary fiber of sisal waste and Moringa stems by ultrasonic-assisted enzymatic method, all of which applied a constant frequency of 20 kHz. The constant low frequency may be chosen because the ultrasonic frequency is inversely



proportional to the duration of sparse phase, and the formation and growth of cavitation bubbles need a certain compression sparse cycle time. If the compression sparse cycle time is too short, cavitation bubbles will not form and grow, and a large number of bubbles formed at high frequency will also hinder mass transfer.

The extraction and modification of dietary fiber by ultrasonic frequency is indeed an important research direction in the field of food processing in the future. Its core advantage lies in effectively improving the extraction rate, solubility and functional characteristics of dietary fiber without using chemical reagents through physical mechanisms such as cavitation effect, mechanical shear and thermal effect.

## 5.2 Ultrasonic intensity

Ultrasonic intensity, namely power density, is expressed as power dissipated per second, per liter or per square meter. The intensity of ultrasonic wave increases with the increase of amplitude, and the collapse of cavitation bubbles also increases. However, the yield and modification effect of dietary fiber will not increase when the ultrasonic intensity reaches a certain peak. WANG et al. [50] studied the effects of different ultrasonic wave intensities (10. 18, 12. 22 and 14. 26 W /cm<sup>2</sup>) on the yield of dietary fiber from grapefruit peel. The results showed that the yield of dietary fiber from grapefruit peel increased with the increase of ultrasonic intensity, but it began to decline after the ultrasonic intensity reached 12. 22 W /cm<sup>2</sup>, probably because the ultrasonic intensity was too high. ZHANG et al. [17] measured the weight average molecular weight of apple dietary fiber obtained under different ultrasonic intensities,



which increased with the increase of ultrasonic intensity, but when the intensity exceeded  $302 \text{ W/cm}^2$ , the weight average molecular weight began to decrease.

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### 5.3 Temperature

In a certain range, the yield of ultrasonic extraction of dietary fiber and the effect of modified dietary fiber increased with the increase of temperature, but decreased after reaching the optimal temperature. Zhang et al. [37] studied the effects of ultrasonic temperature at  $50^\circ\text{C}$ ,  $55^\circ\text{C}$ ,  $60^\circ\text{C}$ ,  $65^\circ\text{C}$  and  $70^\circ\text{C}$  respectively on the yield of dietary fiber from black bean skin. The results showed that when the temperature was lower than  $60^\circ\text{C}$ , the increase of temperature was beneficial to the extraction of SDF from black bean skin, but when the temperature was higher than  $65^\circ\text{C}$ , the yield decreased. This may be due to the dual effects of dietary fiber and solvent. On the one hand, the increase of temperature increases the desorption performance and solubility of dietary fiber in the solvent, on the other hand, it reduces the viscosity of the solvent itself and increases the diffusion rate of the solvent in the tissue matrix.

### 5.4 Other factors

Other factors, such as the solvent used for ultrasonic extraction, the ratio of liquid to material, the pH value of the solvent and the treatment time, will also affect the extraction effect to varying degrees. MA R AN et al. [51] extracted pectin from sisal waste at different liquid-material ratios ( $20 : 1$ ,  $30 : 1$  and  $40 : 1$ , mL : g) and at different extraction times (10, 15, 20, 25 and 30 min). The results showed that the maximum yield was  $30 : 1$  when the liquid-material ratio was  $30 : 1$ . LI et al. [24] studied the extraction rate of SDF from apple pomace by ultrasound when the pH



value of the solvent was 1 ~ 5. The results showed that the yield of dietary fiber increased significantly when the pH value increased from 1 to 2, and then the yield decreased with the increase of pH value.

## 6. Conclusion and prospective

As an important functional food ingredient, dietary fiber is widely available, but its high-value application is limited by its low extraction rate, poor solubility and poor taste in natural state. Ultrasonic-assisted extraction and modification technology has brought innovation to dietary fiber industry because of its high efficiency, green and controllable characteristics. By deepening mechanism research, developing joint technology, promoting industrial application and verifying health efficacy, this technology will play a greater role in enhancing the added value of agricultural products and promoting the sustainable development of food industry.

In the future, with the development of intelligent control technology, ultrasonic-assisted extraction will be combined with online monitoring and automatic control to realize precise production. At the same time, interdisciplinary research will further reveal the influence mechanism of ultrasound on the structure-activity relationship of dietary fiber, promote its wide application in the fields of special medical foods, functional drinks and plant-based substitutes, and provide strong technical support for the sustainable development of the global food system.

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## Data Availability Statement

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Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

