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Review Paper/Derleme Makale

Ultrasound-assisted extraction of bioactive compounds from plants

Bitkilerden biyoaktif bileşiklerin ultrases destekli ekstraksiyonu

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Abstract

Objective: This study gives a comprehensive review of the mechanism, advantages and disadvantages of ultrasound-assisted extraction, important factors affecting the ultrasound-assisted extraction of bioactive compounds, and current applications of ultrasound-assisted extraction in extraction of phenolics and flavonoids from plant materials. The primary goal of this review is to gain a thorough understanding of the principles, benefits and impact of ultrasound-assisted extraction on phenolics and flavonoids from plants, investigate the equipment (ultrasonic probe and ultrasonic bath) used in ultrasound-assisted extraction, and provide an overview of ultrasound-assisted extraction in the recovery of phenolic and flavonoid compounds from plants. This review reveals that ultrasound-assisted extraction provides numerous advantages, including its ease of use, increased efficiency and reproducibility, reduced solvent usage, energy consumption, operating costs and processing time, improved product purity, better protection of bioactivity of thermosensitive compounds, and operable at room temperature and atmospheric pressure. Temperature, contact time, solvent type and solvent concentration, solid to solvent ratio, ultrasonic power and ultrasonic frequency are the primary factors affecting ultrasound-assisted extraction of bioactive compounds. Cavitation during ultrasound-assisted extraction accelerates the release of bioactive compounds from plant cells, thus resulting in more efficient extraction.

Conclusion: It is considered that ultrasound-assisted extraction is an innovative method and efficient way to extract bioactive compounds from plants. In conclusion, applications regarding the extraction of phenolic and flavonoid compounds from plants show that ultrasound-assisted extraction is an environmentally friendly method, which is why it is known as green extraction.

Keywords: Ultrasound-assisted extraction, plants, bioactive compounds, phenolics, flavonoids

Öz

Amaç: Bu çalışma, ultrases destekli ekstraksiyonun mekanizması, avantajları ve dezavantajları, biyoaktif bileşiklerin ultrases destekli ekstraksiyonunu etkileyen önemli faktörler ve bitkilerden fenolik ve flavonoidlerin ekstraksiyonunda ultrases destekli ekstraksiyonun mevcut uygulamaları hakkında kapsamlı bir değerlendirme sunmaktadır. Bu derleme çalışmasının temel amacı, bitkilerden fenolik ve flavonoidlerin elde edilmesinde ultrases destekli ekstraksiyonun prensipleri, faydaları ve etkisi hakkında kapsamlı bilgiler vermek, ultrases destekli ekstraksiyonda kullanılan ekipmanları (ultrasonik prob ve ultrasonik banyo) incelemek, bitkilerden fenolik ve flavonoid bileşiklerin geri kazanılmasında ultrases destekli ekstraksiyon hakkında bir bakış açısı sunmaktır. Bu derleme, ultrases destekli ekstraksiyonun kullanım kolaylığı, artan verimlilik ve tekrarlanabilirlik, azaltılmış solvent kullanımı, enerji tüketimi, işletme maliyetleri ve işlem süresi, iyileştirilmiş ürün saflığı, ısıya duyarlı bileşiklerin biyoaktivitesinin daha iyi korunması ile oda sıcaklığında ve atmosferik basınçta çalıştırılabilir olması gibi çok sayıda avantaj sağladığını ortaya koymaktadır. Sıcaklık, temas süresi, çözücü tipi, katı-çözücü oranı, ultrasonik güç ve ultrasonik frekans biyoaktif bileşiklerin ultrason destekli ekstraksiyonunu etkileyen başlıca faktörlerdir. Ultrases destekli ekstraksiyon sırasındaki kavitasyon, bitki hücrelerinden biyoaktif bileşiklerin salınımını hızlandırmakta ve böylece daha verimli bir ekstraksiyon sağlamaktadır.

Sonuç: Ultrases destekli ekstraksiyonun bitkilerden biyoaktif bileşiklerin ekstraksiyonu için yenilikçi bir yöntem ve etkili bir yol olduğu görülmektedir. Sonuç olarak, bitkilerden fenolik ve flavonoid bileşiklerin ekstraksiyonuna ilişkin uygulamalar, ultrases destekli ekstraksiyonun çevre dostu bir yöntem olduğunu ve bu nedenle yeşil ekstraksiyon olarak bilindiğini göstermektedir.

Anahtar kelimeler: Ultrases destekli ekstraksiyon, bitkiler, biyoaktif bileşikler, fenolikler, flavonoidler

1. Introduction

Extraction of bioactive compounds from plants can be defined as a separation process to obtain plant ingredients and make them useful for a wide range of applications. Numerous substances found in plants have been documented as bioactive components including antioxidants (Zhang et al., 2021), nutraceuticals (Chen et al., 2021), antimicrobials (Pham et al., 2021) and other bioavailable constituents (Aekthammarat et al., 2020). Plants have a powerful antioxidant defense system that includes enzymes and metabolites. Antioxidants are bioactive compounds that can prevent or delay the oxidation of other molecules. The two main water-soluble antioxidant metabolites are ascorbate and glutathione, but secondary metabolites including polyphenols, flavonoids and terpenoids also help detoxify reactive oxygen species under various environmental stresses. Plant extracts rich in bioactive compounds have long been known as commercial ingredients in the food, nutraceutical, cosmetic and pharmaceutical industries because many plant secondary metabolites have antioxidant activity (Stagos 2020; Yusoff et al., 2022).

Methods for extracting bioactive compounds can be classified as conventional solid-liquid extraction techniques (percolation, maceration, decoction, soxhlet extraction, hydro distillation and solvent extraction techniques) and non-conventional methods (microwaves, ultrasound, supercritical fluid, high pressure liquid, pulsed electric field and enzyme-assisted extraction techniques). Conventional solid-liquid extraction techniques have some drawbacks such as low selectivity and low recovery percentages or extraction yields, very laborious and time-consuming, usually require high temperatures that degrade thermosensitive compounds, energy intensified processes and use large amounts of organic solvents that in many cases can be toxic and may remain in trace quantities in the extracts (Agregán et al., 2021; Sridhar et al., 2021; Yusoff et al., 2022). As compared to conventional solid-liquid extraction techniques, ultrasound-assisted extraction has many advantages including ease of operation, higher efficiency and reproducibility, shorter processing time, lower operating costs, less solvent usage, higher product purity, less energy consumption and better protection of bioactivity of thermosensitive compounds, and can be done at room temperature and atmospheric pressure (Freitas de Oliveira et al., 2016; Fu et al., 2021; Lama-Muñoz and Contreras, 2022; D. Mehta et al., 2022; N. Mehta et al., 2022; Pagano et al., 2021). The pressure created during sonic cavitation by ultrasonic waves accelerates mass transport, which releases the extractable materials to the medium more quickly than the conventional solid-liquid extraction (Ashokkumar, 2015; Medina-Torres et al., 2017; Tiwari, 2015). On the other hand, one of the most important disadvantages of the ultrasound-assisted extraction is that it may oxidize lipids and unsaturated fatty acids, and produce free radicals.

The purpose of this study is to give information on the mechanism, factors affecting the ultrasound-assisted extraction of bioactive compounds, and current applications of ultrasound-assisted extraction in extraction of phenolics and flavonoids from plant-based materials. The novelty of this review lies on the fact that it presents new information and recent literature in ultrasound-assisted extraction of phenolics and flavonoids from plants by overviewing a wide range of possibilities for the extraction of plant-based bioactive compounds using ultrasound-assisted technology. This review addresses important issues that need to be considered in ultrasound-assisted extraction of bioactive compounds from plants, and provides guidance and knowledge in understanding the ultrasound-assisted technology.

2. Mechanism of ultrasound-assisted extraction

Ultrasound-assisted extraction is environmentally friendly technology so it is considered as a green extraction technology (D. Mehta et al., 2022; Pagano et al., 2021). Ultrasound-assisted extraction is a method that involves the interaction of ultrasound power with solvents to extract biologically active compounds from plant materials (Freitas de Oliveira et al., 2016). The mechanism of ultrasound-assisted extraction is based on the formation of bubbles, creating cavitation effect, thus leading to mechanical and thermal effects on plant cells. These effects disrupt or break down cell walls of plant, enabling the release of bioactive compounds into the solvent through diffusion and/or dissolution (Bi et al., 2019; Qian et al., 2020). Ultrasound consists of mechanical waves with frequencies higher than the human audible range (≥ 20 kHz). These waves create compression and rarefaction cycles that propagate through a medium, causing molecular movement. High-intensity sound waves induce cavitation bubbles during rarefaction, pushing molecules apart and forming bubbles. These bubbles coalesce and collapse during compression, generating extreme localized conditions with temperatures reaching up to 5000 K and pressures up to 1000 atm. These conditions accelerate biochemical reactions in the surrounding area (Chemat et al., 2017a). Ultrasound-assisted extraction methods can have processes that may involve single or multiple mechanisms (Chemat et al., 2017b). These mechanisms include fragmentation, erosion, capillary action, tissue disruption and ultrasound perforation. Combining these mechanisms enhances ultrasound intensity, promoting cell destruction and mass transfer (Zahari et al., 2020). Ultrasound energy creates voids and microscopic channels, facilitating water removal (Chen et al., 2020). These voids and channels increase the contact area between bioactive compounds and solvents, accelerating the mass transfer phenomenon. The schematic representation of the mechanism of ultrasound-assisted extraction is depicted in Figure 1.

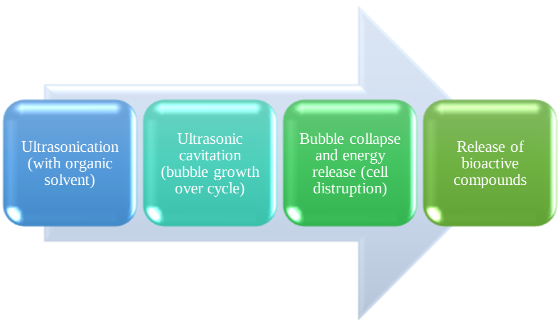

Figure 1. Mechanism of ultrasound-assisted extraction

3. Factors affecting ultrasound-assisted extraction of bioactive compounds

Bioactive compounds are incorporated into various products such as prepared foods, herbal supplements, teas, concentrates, flavors and colors. Plant extracts, rich in bioactive compounds, have become important in the food and nutraceutical industries due to their diverse applications, where the ultrasound technology facilitates the extraction of bioactive compounds through cavitation (Yusoff et al., 2022). Various factors such as temperature, time, solvent properties, solid to solvent ratio, ultrasonic power and ultrasonic frequency affect ultrasound-assisted extraction of bioactive compounds (Coelho et al., 2021; Liao et al., 2021; Lin et al., 2021; Mahindrakar and Rathod, 2020; Muñiz-Márquez et al., 2013; Ozdemir et al., 2024; Wani and Uppaluri, 2022; Yu et al., 2019) (Figure 2).

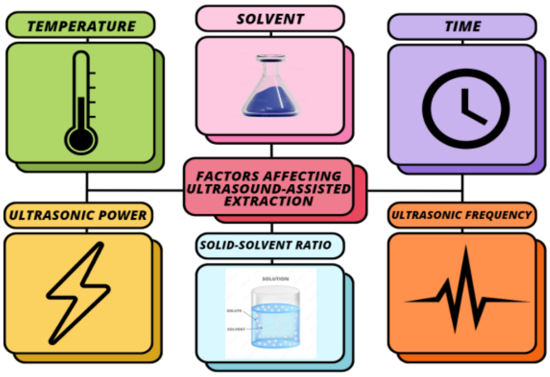

Figure 2. Factors affecting ultrasound-assisted extraction

Temperature affects the extraction rate and the stability of the compound extracted (Bouafia et al., 2021; Coelho et al., 2021; Mai et al., 2020; Yu et al., 2019). Lower temperatures are preferred to preserve heat-sensitive compounds, but moderate heating usually increase solubility of bioactive compounds (Brahmi et al., 2022; Ozdemir et al., 2024; Tanase et al., 2018). Ultrasound treatment increases temperature so cooling is usually required to keep the temperature constant. Contact time has an effect on extraction efficiency, which increases with an increase in extraction time, but longer contact times may cause degradation or loss in bioactivity of phenolics and flavonoids (Coelho et al., 2021; Turker and Isleroglu, 2021; Wani and Uppaluri, 2022). Solvent type and solvent concentration significantly affect solubility and compound interactions, have an influence on the recovery of phenolic and flavonoid compounds from plants and require specific selection for the extraction of bioactive compounds (Brahmi et al., 2022; Muñiz-Márquez et al., 2013; Sim et al., 2019; Tanase et al., 2018). Solid to solvent ratio, which defines the ratio of plant material to solvent, affects extraction efficiency and productivity (Clodoveo et al., 2022; Lin et al., 2021; Mahindrakar and Rathod, 2020; Yang et al., 2019). Although higher ratios offer more surface area for interaction, excessive amounts can cause saturation. Ultrasound power or power density measured usually in watts directly affects extraction efficiency by increasing the cavitation intensity (Coelho et al., 2021; Liao et al., 2021; Lin et al., 2021; Mahindrakar and Rathod, 2020; Yang et al., 2019). Higher power densities can lead to more intense cavitation and therefore more effective extraction. Care should be taken to balance efficiency and product quality. Ultrasound frequency, which represents the oscillation per second of ultrasound waves, also affects extraction efficiency (Liao et al., 2021; Ozdemir et al., 2024). Higher frequencies intensify cavitation effects, facilitating cell lysis and mass transfer, thus increasing extraction efficiency. Therefore, it is important to find the appropriate frequency to prevent damage to bioactive compounds. Optimization of the factors affecting the ultrasound-assisted extraction maximizes extraction efficiency while maintaining the integrity and activity of the extracted substances, paving the way for sustainable and high-quality extraction practices.

4. Ultrasound-assisted extraction with ultrasonic probe and ultrasonic bath

Ultrasound-assisted extraction can be performed with an ultrasonic probe (Figure 3) or ultrasonic bath (Figure 4). Ultrasonic power and frequency are adjusted within a certain range in an ultrasonic probe, thus allowing higher extraction rates and product quality. Ultrasonic probe, when integrated into mixing, helps in better distribution of components and homogenization of food products. Accelerated mass transfer improves extraction by disrupting cellular structures, increasing surface area, and facilitating the release of flavors, nutrients and bioactive compounds (Rao et al., 2021). Ultrasonic probe is also effective in cleaning food processing equipment by generating cavitation bubbles that remove dirt, oil, microorganisms and biofilms from food processing equipment surfaces (Zhou et al., 2022). Ultrasonic probe can be integrated into a temperature controlled water bath, which allows for precise temperature control during processing, providing optimal conditions for enzymatic reactions, pasteurization, sous vide cooking and other thermal processes (Yusoff et al., 2022). Improved penetration of heat into food products is achieved by disrupting barriers like air pockets or membranes, resulting in more uniform heating and shorter processing times (Wen et al., 2018).

Figure 3. Ultrasonic probe

Ultrasonic baths typically function using liquids housed in a metal or plastic container. The liquid is commonly water or water-based solution, where the food material is immersed. The ultrasound transducers in the apparatus convert electrical energy into ultrasound waves, but usually ultrasonic power and frequency are not tunable, which is the most important disadvantage of the ultrasonic bath (Wen et al., 2018). Non-uniform energy distribution affects efficiency of ultrasonic baths when compared to ultrasonic probe systems (N. Mehta et al., 2022). Therefore, extraction efficiency and yield are lower than that of the ultrasonic probe (Rao et al., 2021).

Figure 4. Ultrasonic bath

5. Extraction of plant bioactive compounds with ultrasound-assisted technology

5.1. Phenolics

Natural phenolic compounds are a complex class of substances that range from monomers like phenolic acids to highly polymerized molecules like tannins. They are primarily found in conjugated forms, with one or more sugar units (monosaccharides, disaccharides and even oligosaccharides) bound to hydroxyl groups. It is also frequently linked with other chemicals such as carboxylic acids, amines and lipids as well as with other phenols. Especially given the complexity of plant matrices, extraction methods for phenolic compounds have attracted considerable attention in recent years due to the intriguing bioactive properties, health benefits and potential applications of phenolics. At the cellular level, hydrophilic phenolic compounds (e.g., phenolic acids, anthocyanins and low molecular weight tannins) are primarily found in vacuoles, whereas insoluble phenolic compounds (e.g., condensed tannins, phenolics covalently bound to insoluble polymers such as polysaccharides or proteins forming stabilized macrocomplexes) are typically found in cell walls (Lama-Muñoz and Contreras, 2022). Phenolics are characterized by one or more aromatic rings linked to one or more hydroxyl groups (Alara et al., 2021). Plants create phenolic compounds, and they are genetically regulated both qualitatively and quantitatively. Furthermore, phenolic compounds function as antioxidants, antimicrobials, UV radiation protectors, nutrient enhancers, flavoring agents and colorants for various plants. Conversely, phenolic molecules that undergo oxidation are transformed into quinones, which are associated with an unfavorable brown color.

Extraction is the primary step in recovering and purifying phenolic compounds from plant materials prior to analysis and application because it allows for the concentration of these compounds while reducing interfering substances. The extraction of phenolic compounds is especially important when conducting quantitative investigations because their tissue distribution in plants is not homogeneous.

Sonication influences the physical phenomena that affect the extraction of phenolic compounds, which are generally located inside of the plant tissue cells. Ultrasound-assisted extraction uses high-frequency sounds (between 20 and 40 kHz) to release phenolic compounds from plants, but higher frequencies can also be used (Pagano et al., 2021). The influence of applying ultrasound waves to the extraction medium and matrix may favor not only the extraction of phenolic compounds but also the development of secondary reactions that result in a decrease in the phenolic concentration (Lama-Muñoz and Contreras, 2022). Antioxidant activity is a property of great importance in the case of phenolic compounds. The area of exposure to the solvent and the cavitation increase as the particle size of the plant material is reduced, thus resulting in higher extraction efficiency. Pre-treatments can also improve the recovery and yield of phenolic compounds from plants (Sentkowska et al., 2024). Ultrasound-assisted extraction of phenolic compounds from different plants is summarized in Table 1.

5.2. Flavonoids

Flavonoids, one of the subclasses of phenols that regulate the physiological functions of plants, contain many polyphenols characterized by the benzo-γ-pyrone structure (Yusoff et al., 2022). Flavonoids are polyphenolic compounds synthesized as bioactive secondary metabolites in plants and are responsible for color, taste and antioxidant activity (Liga et al., 2023). The main sources of flavonoids are fruits and vegetables. Among fruits, plums, cherries and apples are very rich in flavonoids while tropical fruits are poor in flavonoids. Notably, vegetables like beans, olives, onions, shallots, spinach, lettuce, cabbage, celery, broccoli and hot peppers boast high concentrations of flavonoids. There are also plenty of flavonoids in cocoa products, chocolate, black tea and green tea. Flavonoids play a crucial role in conferring properties such as color, taste, prevention of lipid oxidation, enzyme protection and physiological stress resistance in plants (Kopustinskiene et al., 2020). They are the primary contributors to the vibrant colors observed in plant tissues. Functioning as potent antioxidants, flavonoids serve to shield plants from unfavorable environmental conditions. The amount of flavonoids synthesized is influenced by various factors, including plant cultivar/genotype, growing conditions, soil characteristics, harvest and storage (Dias et al., 2021).

Both humans and animals are not able to synthesis flavonoids. Nonetheless, flavonoids are an essential component of the diets of mammals. Flavonoids are utilized in the food, cosmetic and pharmaceutical industries because of their exceptional antioxidant properties. Because flavonoids may both neutralize and prevent the generation of free radicals, they are thought to be potential natural antioxidants. The presence of free hydroxyl groups and phenolic rings in the chemical structure of flavonoids is primarily responsible for their antioxidant activity. Free hydroxyl groups can donate hydrogen, thus preventing oxidation. Extraction techniques with high yield and purity are required for the industrial use of antioxidants. In recent years, ultrasound-assisted extraction is becoming a more favorable extraction method over the other environmentally friendly extraction techniques (Rodríguez De Luna et al., 2020). Ultrasound-assisted extraction of flavonoid compounds from different plants is summarized in Table 2.

Table 1. Ultrasound-assisted extraction of phenolic compounds from plants

Source	Ultrasonic equipment	Extraction conditions	Results	References
Laurus nobilis L. leaves	Ultrasonic probe	Extraction temperature: 25°C Extraction time: 20, 40 and 60 min Ethanol/water concentration: 0, 35 and 70% Solid/solvent ratio: 1:4, 1:8 and 1:12 g/mL Ultrasound frequency: 40 kHz	The best extraction conditions for phenolic compounds were extraction time of 40 min, ethanol concentration of 35% and solid/solvent ratio of 1:12 g/mL.	Muñiz-Márquez et al. (2013)
Beech (*Fagus sylvatica* L.) bark	Ultrasonic bath	Extraction temperature: 50, 60 and 80°C Extraction time: 15, 30 and 45 min Ethanol/water concentration: 50 and 70% Ultrasound frequency: 40 kHz	The maximum total phenolic content was obtained at 60°C, 15 min and ethanol concentration of 70%.	Tanase et al. (2018)
Kenaf *(Hibiscus cannabinus* L.) leaves	Ultrasonic probe	Extraction temperature: 18-22°C Extraction time: 1 min pulse duration period Extraction solvent: Water, methanol, ethanol and acetone Ultrasound amplitude: 50%	Ethanol was the most effective solvent for the extraction of phenolic compounds.	Sim et al. (2019)
Common bean (*Phaseolus vulgaris* L.)	Ultrasonic bath	Extraction temperature: 30 and 50°C Extraction time: 40 and 80 min Acetone/water concentration: 40 and 60% Solvent/solid ratio: 30:1 and 40:1 mL/g Ultrasound power: 400 and 560 W	Extraction temperature of 30°C, extraction time of 68 min, solvent concentration of 55%, solvent/solid ratio of 36:1 mL/g and ultrasonic power of 480 W yielded the maximum total phenolic content.	Yang et al. (2019)
Centaurea sp. leaves	Ultrasonic bath	Extraction temperature: 45, 50 and 55°C Extraction time: 20, 30 and 40 min Solid/solvent (methanol) ratio: 0.5:45, 0.5:50 and 0.5:55 g/mL Ultrasound frequency: 40 kHz	The maximum total phenolic content was obtained at 54.9°C, 39.9 min and solid/solvent ratio of 0.5:53.9 g/mL.	Bouafia et al. (2021)
Strawberry guava leaves	Ultrasonic probe	Extraction temperature: 40, 50 and 60°C Solid/solvent (hexane) ratio: 1:10, 1:15 and 1:20 g/mL Ultrasound power: 100, 300 and 500 W	The highest yield for phenolics was observed at 40°C, solid/solvent ratio of 1:20 and ultrasound power of 500 W.	Coelho et al. (2021)
Opuntia ficus-indica flower	Ultrasonic bath	Extraction temperature: 30-70°C Extraction time: 10-60 min Ethanol/water concentration: 20-100% Ultrasound frequency: 50 kHz	The optimal extraction conditions for phenolics were 53°C, 60 min and 36% ethanol concentration.	Brahmi et al. (2022)
Ceratonia siliqua	Ultrasonic bath	Solid/solvent ratio: 1:0.05-1:0.2 g/mL Ethanol/water concentration: 0-100% Particle size: 0.3-2 mm Extraction temperature: 35°C Extraction time: 15 min Ultrasound power: 100 W Ultrasound frequency: 37 kHz	The best results for phenolic compounds were obtained at solid/solvent ratio of 1:0.2 g/mL, ethanol/water concentration of 40% and particle size of 0.3 mm.	Clodoveo et al. (2022)
Galangal (*Alpinia officinarum*)	Ultrasonic probe	Extraction temperature: 20-70°C Extraction time: 5-60 min Ethanol/water concentration: 10-90% Solvent/solid ratio: 5:1-40:1 mL/g Ultrasound power: 10-90% Ultrasound cycle: 1-9	Temperature of 25°C, extraction time of 20 min, ethanol/water concentration of 50%, solvent/solid ratio of 10:1 mL/g, ultrasound power of 50% and ultrasound cycle of 5 were determined to be the most efficient extraction conditions for total phenolic compounds.	Ozdemir et al. (2024)

Table 2. Ultrasound-assisted extraction of flavonoid compounds from plants

Source	Ultrasonic equipment	Extraction conditions	Results	References
Kenaf (Hibiscus cannabinus L.) leaves	Ultrasonic probe	Extraction temperature: 18-22°C Extraction time: 1 min pulse duration period Extraction solvent: Water, methanol, ethanol and acetone Ultrasound amplitude: 50%	Ethanol was the most effective solvent for the extraction of flavonoid compounds.	Sim et al. (2019)
Crinum asiaticum	Ultrasonic bath	Extraction temperature: 30-70°C Extraction time: 10-80 min Ethanol/water concentration: 30-80% Solid/solvent ratio: 1:10-1:50 Ultrasound power: 180 W Ultrasound frequency: 40 kHz	The best conditions for maximum flavonoid yield were at 64°C extraction temperature, 47 min extraction time, 60% ethanol concentration and 1:28 solid/solvent ratio.	Yu et al. (2019)
Euonymus alatus	Ultrasonic bath	Extraction temperature: 35-95°C Extraction time: 5-25 min Polyethylene glycol 400/water concentration: 8-24% Solvent/solid ratio: 30:1-70:1 mL/g Particle size: 40-120 mesh	The optimum extraction conditions for flavonoids were obtained at extraction temperature of 90 °C, extraction time of 15 min, PEG-400 concentration of 16%, solvent/solid ratio of 60:1 mL/g and particle size of 80 mesh.	Mai et al. (2020)
Syzygium cumini seed kernel powder	Ultrasonic bath	Extraction temperature: 25-65°C Extraction time: 0-20 min Solid/solvent (water) ratio: 1:05-1:50 g/mL Ultrasound power: 44-215 W Ultrasound cycle: 10-100% Ultrasound frequency: 22 kHz	Extraction temperature of 35°C, extraction time of 12 min, solid/solvent ratio of 1:15 g/mL, ultrasound power of 125 W and ultrasound cycle of 60% yielded the maximum total flavonoid content.	Mahindrakar and Rathod (2020)
Moringa oleifera leaves	Ultrasonic bath	Extraction temperature: 30°C Extraction time: 20 min Ethanol/water concentration: 30, 45 and 60% Solvent/solid ratio: 30:1, 35:1 and 40:1 mL/g Ultrasonic power: 80, 160 and 240 W	The flavonoid compounds were reached the optimal values at ultrasonic power of 188 W, solvent/solid ratio of 40:1 mL/g and ethanol concentration of 52%.	Lin et al. (2021)
Peanut shell	Ultrasonic bath	Extraction temperature: 25-70°C Extraction time: 0-80 min Ethanol/water concentration: 50-80% Solvent/solid ratio: 10:1-60:1 mL/g Particle size: 0.095-0.995 mm Ultrasound power: 90-210 W Ultrasound frequency: 20-60 kHz	The maximum total flavonoid content was obtained at extraction temperature of 55°C, extraction time of 80 min, ethanol concentration of 70%, solvent/solid ratio of 40:1 mL/g, particle size of 0.285 mm, ultrasound power of 120 W and ultrasound frequency of 45 kHz.	Liao et al. (2021)
Artichoke (*Cynara scolymus*) leaves	Ultrasonic probe	Extraction temperature: 25°C Extraction time: 20-60 min Extraction solvent: Distilled water Ultrasound power: 500 W Ultrasound frequency: 20 kHz Ultrasound amplitude: 30-80%	The best extraction conditions for flavonoids were 20 min of extraction time and 65% of ultrasound amplitude.	Turker and Isleroglu (2021)
Psidium guajava leaves	Ultrasonic bath	Extraction temperature: 40-70°C Extraction time: 5-20 min Extraction solvent: Distilled water Solid/solvent ratio: 0.02:1-0.2:1 g/mL Ultrasound power: 80 W Ultrasound frequency: 37 kHz	The highest total flavonoid compounds were obtained at extraction temperature of 62.19°C, extraction time of 14.94 min and solid/solvent ratio of 0.19 g/mL.	Wani and Uppaluri (2022)
Galangal (*Alpinia officinarum*)	Ultrasonic probe	Extraction temperature: 20-70°C Extraction time: 5-60 min Ethanol/water concentration: 10-90% Solvent/solid ratio: 5:1-40:1 mL/g Ultrasound power: 10-90% Ultrasound cycle: 1-9	The most efficient extraction conditions for total flavonoid compounds were temperature of 25°C, extraction time of 20 min, ethanol/water concentration of 50%, solvent/solid ratio of 10:1 mL/g, ultrasound power of 50% and ultrasound cycle of 5.	Ozdemir et al. (2024)

6. Conclusion

Plant bioactive compounds such as phenolic and flavonoid compounds are valuable ingredients in the formulation of foods, nutraceuticals, cosmetics, and medicinal and pharmaceutical products. The ultrasonic bath and probe are often employed to induce acoustic cavitation, which can disrupt the chemical bonds of bioactive substances. Ultrasound-assisted extraction, a green technology and non-thermal method, has significant benefits for the food industry. Research has revealed that ultrasound-assisted extraction is an effective tool to obtain bioactive compounds from various plant-based sources as compared to traditional extraction methods. The ultrasound-assisted extraction is an emerging extraction method with superior advantages such as reduced extraction time, lower solvent consumption, higher product purity, less energy consumption, higher yield as well as minimizing the degradation of heat-sensitive compounds and better protection of bioactivity of heat-labile components. However, the processing parameters used in the ultrasound-assisted extraction process affect its efficiency in terms of recovery of phenolics and flavonoids, and their bioactivities. As a result, improving ultrasound-assisted extraction conditions is required to obtain bioactive compounds with better quality and higher yield because extraction conditions vary depending on the characteristics of plant material. The findings reported in this study regarding ultrasound-assisted extraction of phenolics and flavonoids from plants contribute significantly to existing knowledge and literature. In conclusion, this study highlights the importance of ultrasound-assisted extraction in releasing of bioactive compounds, paving the way for innovative applications, and advancing the understanding of sustainable and efficient extraction methods.

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