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# Ultrasonic assisted medicinal plant extraction: The review

Thandar Aung * and Sreemoy Kanti Das

*Faculty of Pharmacy, Lincoln University College, Selangor, Malaysia.*

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## Abstract

The extraction of bioactive compounds from medicinal plants plays a pivotal role in the development of pharmaceutical, nutraceutical, and cosmetic products. Conventional extraction methods, although widely used, often suffer from limitations such as prolonged extraction times, high solvent consumption, and degradation of thermolabile compounds. Ultrasonic-assisted extraction (UAE) has emerged as a green, efficient, and scalable alternative, leveraging acoustic cavitation to enhance mass transfer and disrupt plant cell walls. This review comprehensively discusses the fundamental principles of UAE, including the role of ultrasonic frequency, power intensity, solvent type, and extraction duration. Comparative analysis with traditional techniques demonstrates UAE's superiority in terms of yield, time efficiency, and energy conservation. Recent advancements in reactor design, hybrid systems, and statistical optimization (e.g., response surface methodology) are highlighted. Limitations related to equipment scale-up, process reproducibility, and bioactive stability are critically addressed. Finally, future directions include the use of green solvents and AI-driven modeling for industrial-scale optimization. This review provides researchers and industry stakeholders with an in-depth understanding of UAE as a sustainable, high-performance technology for the extraction of medicinal plant bioactive.

**Keywords:** Ultrasonic-Assisted Extraction (UAE); Medicinal Plants; Green Extraction Technologies; Cavitation; Phytochemicals; Bioactive Compounds

## 1. Introduction

For many years, traditional medicine has utilized plants for medicinal purposes to cure many illnesses. Centaurium erythreae Pers. - anti-inflammatory, antipyretic, hypoglycemic, antioxidant, antimicrobial, hepatoprotective, gastroprotective, etc. [1]; Glycyrrhiza glabra L. - anti-inflammatory, antiulcer, expectorant, antimicrobial, and anxiolytic activities [2]; Silene vulgaris (Moench) Garcke - good for bronchitis and asthma [4]; Aspalathus linearis L. - relieves allergies, dermatological issues, asthma, infantile colic, and other gastrointestinal complaints, such as nausea and heartburn [5,6]; and Sambucus nigra L. - beneficial effects on blood pressure, glycaemia reduction, immune system stimulation, antitumor potential, increase in the activity of antioxidant enzymes in the blood plasma, including glutathione, and the reduction of uric acid levels [7].

Nonetheless, a remarkable number of herbal plants with therapeutic benefits have far higher levels of bioactives, which work in concert with the human body to provide special therapeutic benefits with few negative side effects. For example, tulsi, neem [8], ashwagandha [9], rosemary [10], thymus fon tanesii [11], eucalyptus [12], turmeric root [13], coriander [14], and others are common medicinal and herbal plants that contain bioactives.

Ultrasonic-assisted extraction (UAE) has been shown to be a highly effective technique for boosting yield while using less solvent and reducing heat damage [15]. Through sonic cavitation, ultrasound, a non-thermal process intensification technique, improves extraction by increasing solvent penetration and solute diffusion [16]. In order to maximize UAE,

* Corresponding author: Thandar Aung

variables including temperature, power, and time must be changed. This can increase the yields of saponins. Finding the ideal circumstances for maximal yield and purity is made easier with the use of response surface methodology (RSM) [17]. Since separation and purification concentrate these bioactive ingredients and increase their therapeutic efficacy, they are equally important [18].

Free radicals are unstable chemicals created by both internal processes like metabolism and external factors like pollution and UV rays. Antioxidants are molecules that help protect the body's cells from these harmful effects. The oxidative stress that free radicals can cause can lead to aging, inflammation, cell damage, and a variety of illnesses, such as cancer, heart disease, and neurological issues. to break down cell walls and improve the release of bioactive chemicals by creating sonic cavitation in the extraction media [19]. In order to generate high-quality, target-rich chemical extracts in shorter extraction times with little to no use of organic solvents, UAE is also essential for phenolic component extraction from samples [20, 21].

The focus of this review is on yet unexplored ultrasound-assisted technologies that extract bioactives from widely accessible medicinal plants. In this review, we will address UAE's technological features, mechanistic knowledge, crucial components, and bioactives thoroughly and up-to-date.

## 2. Ultrasound assisted extraction

### 2.1. Extraction mechanisms

The fundamental idea behind ultrasonic extraction technology is to increase extraction efficiency by using the cavitation, mechanical, and thermal effects of ultrasound to speed up the release, diffusion, and dissolution of useful compounds inside the cell. The cavitation phenomena is the result of a medium being ripped apart by high-energy ultrasonic waves into numerous tiny cavities that immediately shut, creating an instantaneous pressure of up to millions of atmospheres. The fragmentation time is shortened by the tremendous pressure created by the tiny bubbles in cavitation bursting, which causes the plant cell walls to shatter and the entire organism to be completed in a single instant. Simultaneously, the ultrasonic vibration improves intracellular substance release, diffusion, and dissolution, which greatly increases extraction efficiency [22–24] (Figure 1). The chemical effect of cavitation may be attributed to greater free radical generation, degrading target molecules [25]. Mechanical forces remove bioactive chemicals from vegetal tissue in two stages. Mechanical effects allow solvent to permeate the cell wall and damage the acellular matrix, reducing particle size [26]. Thus, the solution diffuses fast from plant tissues to solvent with enhanced mass transfer across plant membranes until equilibrium is reached [27].

The primary purpose of this ultrasonic intensity is to find information about the chemical and physical characteristics of plants extract. Low-frequency ultrasound, which has a substantial vibration effect, operates at frequencies between 20 and 100 kHz. Large vibration force and enhanced mechanical effect are conveyed to the generator, which generates high energy and raises the system's temperature while encouraging mass transfer. Additionally, the use of ultrasound treatment has high repeatability, low dependence on reagents, and simpler subsequent processing of the product [28]. Ultrasound has many benefits in food processing, including more thorough mixing of various substances, lowering processing temperature, promoting mass transfer, shortening processing time, and increasing extraction efficiency.

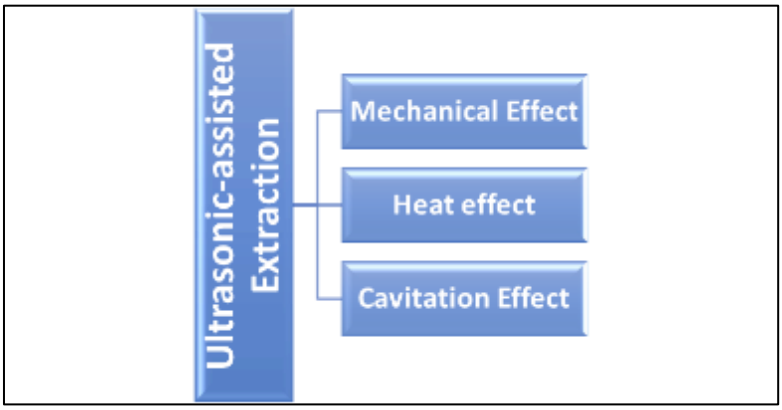


**Figure 1** Ultrasonic-assisted extraction technology [24]

### 2.2. Ultrasound devices

Considering the effects so far, ultra sound may be a potential technique to introduce equipment into extraction procedures. Samples can be affected directly or indirectly by ultrasound. Direct sound wavelength impacts occur directly on samples, while indirect effects occur through containers before reaching samples. Some investigations found that ultrasound probes (horns) increased mass transfer. The absence of ultrasound propagation impediments may explain these improvements. Ultrasound processes, usually done in ultra sound baths or powerful ultrasound reactors, indirectly affect samples. The sample container had lower ultrasound intensity than expected because ultrasound waves had to pass through the liquid in the ultrasonic device and then through the container wall [29]. Some current applications require an ultrasonic probe instead of an ultrasound bath.

The compression and rarefaction cycles (high and low-pressure regions) that comprise ultrasound waves can travel through solid, liquid, or gaseous media, dislodging and dislocating molecules from their initial positions and producing enormous amounts of energy [30]. Furthermore, cavitation bubbles appear when high-intensity negative pressure is applied because the rarefaction cycle exceeds the liquid molecules' attraction forces [31]. While ephemeral cavitation or inertial cavitation bubbles persist for a very brief period, frequently less than a single cycle, and then rapidly disintegrate, stable cavities, which are long-lasting gas bubbles, are produced by several compression and rarefaction cycles of sonication [32].

#### *2.2.1. The ultrasonic bath*

Ultrasonic baths are effortless to use and cost-effective, but the solvent and experimental glassware greatly reduce the ultrasonic strength, making them unsuitable for chemical reactions [33]. Indirect extraction gives good results in the ultrasonic bath, but only a modest number of bioactive substances may be extracted. Direct extraction yields more. Other researchers found that particle size, acid and/or oxidant used, leaching volume, sonication time, water temperature inside the bath, ultrasonic frequency, sample position (vertical or horizontal) and detergent use in the water greatly affect the sonication bath [34, 35]. The above factors improve ultrasound transmission. Ultrasound bath systems also have an ultrasonic sounder that generates an excitation signal that matches the tuning assembly's modal frequencies.

The extraction cell design, which reduces ultrasonic power, is the hardest part of any ultrasound-assisted system. In bath-type sonication, the thick walls of the extraction cell bear the pressure, attenuating ultrasonic waves from the transducers and limiting influence on the extraction medium [36]. Piezoelectric transducers turn electricity into mechanical vibrations. In non-contact applications, tuning devices transfer mechanically generated ultrasonic waves to airborne material. Ultrasound transmission depends on the propagation medium's acoustic impedance. The difference between the ultrasonic transducer material's impedance and air's greatly affects non-contact ultrasonic wave use.

#### *2.2.2. The ultrasonic probe*

The probe system is commonly used to sonicate tiny samples. Because ultrasonic strength is conveyed exclusively at the probe tip, probe-type ultrasound is stronger than ultrasound bath. Probe sonication raises sample temperatures sharply. Thus, ultrasonography equipment design matters. In early ultrasonic chemistry, an open beaker was immersed directly in an ultrasonic bath and the influence of ultrasonic probes on reproducibility was examined [37]. With improved ultrasound generators, the piezoelectric transducer could directly enter the ultrasonic solvent. This device accelerates mass transfer but increases sample destruction due to ultrasonic probe degradation [38, 39]. Given the uniformity of the equipment's pressure field, the reactor size and element relative to the sensor must be calculated to maximize energy transfer to fluid. This optimizes extraction efficiency. Mapping can enhance cavitation to test reactor dimensions and transducer positions.

Ultrasonic probes provide more ultrasound power than ultrasound baths because they directly submerge in the solution for sonication and improve material contact area to reduce mass transfer resistance. Note that certain settings may alter the ultrasonic probe: amplitude, temperature, reaction vessel shape, diameter, unit, probe type, and material chemical characteristics. The ultrasound cavitation effect is also affected by the response vessel form, which must be conical and have a small diameter to raise the level and allow the probe to be inserted deeper into the sample. Due to foaming and corrosion in some samples, sonotrode material and diameter are crucial. Heat- and corrosion-resistant titanium alloy probes are common [40]. However, the ultrasonic probe can directly contact the sample in the pressured vessel [41].

## 3. Ultrasonic assisted medicinal plant extraction

Ultrasonic-assisted extraction (UAE) has emerged as a powerful green technology for enhancing the yield and bioactivity of phytochemicals from medicinal plants. Various studies have optimized UAE parameters to improve extraction efficiency, compound stability, and biological activity.

Wang et al. [42] optimized the ultrasonic-assisted extraction of rutin from Ilex asprella using deep eutectic solvents (DES), applying response surface methodology (RSM). Factors such as solvent type, molar ratio, water content, liquid–solid ratio, ultrasonic temperature, power, and time were studied. A Box–Behnken design identified optimal conditions: lactic acid to choline chloride molar ratio of 1:1, 40 °C extraction temperature, 31 min duration, 28% water content, and a 20:1 mL/g liquid–solid ratio. Under these parameters, rutin yield was 86.553 ± 1.35 μg/g with <0.6% error from the predicted value. Guan et al. [43] extracted a neutral polysaccharide (PLP-2-1) from Perilla leaves under optimal UAE conditions, followed by sulfation to obtain S-PLP-2-1. Structural analyses (HPLC, methylation, NMR) confirmed high similarity post-modification. Zeta potential, FTIR, thermogravimetric, and rheological analyses supported characterization. Both forms showed antioxidant and hypoglycemic activities. In vitro tests on oleic acid-induced HepG2 cells revealed improved lipid profiles, with enhanced biological effects observed after sulfation, suggesting therapeutic potential against glycolipid metabolic disorders.

Younis et al. [44] investigated Sophora japonica extracts obtained via UAE and formulated them into nanoemulsions. Compared to maceration (51.18 mg GAE/mL), UAE yielded higher phenolic content (65.57 mg GAE/mL), demonstrating superior antioxidant capacity. Legesse et al. [45] optimized UAE for Verbascum sinaiticum, targeting phenolic extraction. Variables included extraction time, temperature, and sample–solvent ratio. UAE outperformed maceration in yield (21.6%), total phenolics (179.8 mg GAE/g), flavonoids (64.49 mg CE/g), and antioxidant activities (DPPH: 61.85 μg/mL, ABTS: 38.89 μg/mL). UHPLC-ESI-QTOF-MS/MS identified 17 phenolics, and SEM confirmed microstructural changes. Optimal conditions were 41.43 °C, 36.32 g/mL sample–solvent ratio, and 33.22 min extraction time, supporting UAE's applicability in pharmaceutical development. Yin and Batbatan [46] established optimal UAE parameters for Portulaca aizoon, achieving a flavonoid yield of 10.77 mg/g under 1 g/55 mL solid–solvent ratio, 60% ethanol, 45 °C, 25 min, and 150 W ultrasound power. The high yield was attributed to extended extraction over three days.

Zhang et al. [47] used enzyme-assisted UAE to extract anthocyanins from Xinjiang mulberries and developed predictive models using RSM and deep neural networks (DNN). Variables included pectinase dosage, hydrolysis time, ultrasonic conditions, solvent concentration, and solid–liquid ratio. Both models were effective, but DNN showed superior accuracy ($R^2$ = 0.9900, error = 0.85%) compared to RSM ($R^2$ = 0.9404, error = 4.50%), highlighting DNN's advantage for precise prediction of optimal extraction outcomes.

Table 1 compiles key studies on ultrasonic-assisted extraction (UAE) of medicinal plants, detailing methodologies, extraction parameters, and yields. It highlights how factors like ultrasonic power, temperature, and time influence the efficiency and effectiveness of bioactive compound recovery.

**Table 1** Ultrasonic Assisted Medicinal Plant Extraction

| References | Medicinal Plant | Methodology | Ultrasonic power | Ultrasound temperature | Extraction time | Extraction yield |
|---|---|---|---|---|---|---|
| Wang et al. [42] | *Ilex asprella* | Box-Behnken Response surface method | 100 W | 40 °C | 31 min | - |
| Guan et al. [43] | *Perilla* leaves | Response surface method | 100 W | 60°C | 6 h | 1.14% |
| Younis et al. [44] | *S. japonica* flowers | Ethanolic maceration method | 600 W | 25 ℃ | 15 min | - |
| Legesse et al. [45] | *Verbascum sinaiticum* (Qetetina or yeahya Joro) | RSM and Maceration extraction | 750 W | 41.43 °C | 33.22 min | 21.6% |
| Li et al. [48] | *Platycodon grandiflorum* roots | Response surface method (RSM) | 153.79 W | 49.59 ℃ | 51.04 min | 4.83 % |
| Chen et al. [49] | Turmeric (*Curcuma longa L.*) | Ionic liquid ultrasound-assisted hydrodistillation | - | 50℃ | 37 min | 6.88 % |
| Souadia et al. [50] | *Thymus algeriensis* | Box-Behnken design (BBD) of response surface methodology (RSM) | - | 60°C | 36.74 min | - |
| Zhou et al. [51] | *Bletilla striata* | Information-dependent acquisition method | 350 W | 5°C | 20 min | - |
| Saeed Abadi et al., [52] | Common horsetail (*Equisetum arvense* L.) | RSM | - | 27.88 °C | 6.91 min | - |
| Lee et al. [53] | *Phedimus aizoon* | UAE | 1500 W | 45°C | 120 min | 16.56% |

Wang et al. [24] reported that Muxu contains over 80 flavonoid-related compounds, including flavonoids and their glycosides, flavonols, isoflavones, chalcones, dihydroflavones, and rosewood-derived compounds. From chloroform and n-butanol extracts of Muxu, seven compounds were isolated and identified: apigenin 7-O-β-D-glucoside, uridine, β-D-glucoside, luteolin-7-O-methyl glucopyranose, apigenin, Muxu extract, and 7,4’-dihydroxyflavone. Younis et al. [43] evaluated the antioxidant activity of Sophora japonica extracts using the DPPH assay. The ultrasound-assisted extract demonstrated a 67% scavenging efficiency, outperforming the ethanolic extract's 59%. Nanoemulsions formulated from the ultrasound extracts showed an average particle size of 252.92 nm and a zeta potential of −36.68 mV, indicating high stability. Over a 5-day oxidative stability test, water-based nanoemulsions maintained structural integrity, while ethanolic formulations exhibited phase separation and increased oxidation.

Zhang et al. [47] determined the optimal conditions for anthocyanin extraction from mulberries using a deep neural network (DNN) model: a solid–liquid ratio of 50 mL/g, ethanol concentration of 63%, ultrasonic temperature of 40 °C, and pectinase dosage of 0.5%. Under these conditions, total anthocyanin content reached 3.16 mg/g. Antioxidant evaluations showed DPPH, ABTS, and hydroxyl radical scavenging rates of 80%, 98%, and 54%, respectively, highlighting the potent antioxidant capacity of mulberry anthocyanins and demonstrating a sustainable, optimized extraction method. Qi et al. [54] used flavonoid extraction from Portulaca aizoon and assessed antioxidant capacity through ABTS and DPPH radical scavenging. At 0.3 mg/mL, P. aizoon extract and vitamin C showed ABTS scavenging

rates of 96.2% and 99.0%, respectively. At 2.0 mg/mL, DPPH scavenging reached 85.9% for the extract and 98.8% for vitamin C, demonstrating strong free radical neutralizing ability of the plant extract, comparable to ascorbic acid.

Hiranpradith et al. [55] optimized UAE parameters for Centella asiatica to maximize total phenolic content (TPC) and total flavonoid content (TFC) using response surface methodology (RSM). Ethanol concentration and solvent volume significantly influenced both TPC and TFC ($p < 0.0001$), while ultrasonic power had minimal impact ($p < 0.05$). Extraction time did not significantly affect TPC ($p > 0.05$) but influenced TFC due to flavonoid degradation ($p < 0.05$). Variable interactions were statistically insignificant ($p > 0.05$). The fitted quadratic models achieved predicted $R^2$ values of 0.8263 for TPC and 0.9006 for TFC. The optimal conditions—75% ethanol, 87.5 W ultrasonic power, 30 min extraction time, and 20 mL solvent volume—yielded TPC and TFC of 52.29 ± 1.65 mg/g and 43.71 ± 1.92 mg/g, respectively. Additionally, Asiatic side and madecassoside yields reached 37.56 ± 4.25 mg/g and 16.91 ± 1.28 mg/g. These findings underscore the efficiency, scalability, and sustainability of UAE for extracting bioactive from C. asiatica, supporting its use in functional food development.

Table 2 summarizes the application of UAE across various medicinal plants, highlighting optimized extraction conditions such as solvent ratios and analytical methods. The table also demonstrates UAE's effectiveness in enhancing antioxidant activity, confirming its potential for high-yield bioactive recovery.

**Table 2** Applications of Ultrasonic-Assisted Extraction (UAE) for Bioactive Compounds from Medicinal Plants: Extraction Conditions and Antioxidant Activities

| Reference | Medicinal Plant | Evaluation of UAE Extracts | Extraction Ratio | Antioxidant Activity |
|---|---|---|---|---|
| Wang et al. [42] | *Ilex asprella* | Rutin yield: 86.553 ± 1.35 μg/g | Liquid–solid ratio of 20:1 mL/g | – |
| Guan et al. [43] | *Perilla* leaves | HPLC, methylation analysis, NMR | Solid–liquid ratio of 1:30 (w/v) | 74.19% |
| Younis et al. [44] | *Sophora japonica* flowers | DPPH assay; TPC: 65.57 mg GAE/mL | – | 67% |
| Legesse et al. [45] | *Verbascum sinaiticum* | TPC: 179.8 mg GAE/g, TFC: 64.49 mg CE/g, DPPH: 61.85 μg/mL, ABTS: 38.89 μg/mL | Sample–solvent ratio: 36.32 g/mL | 38–61% |
| Li et al. [48] | *Platycodon grandiflorum* roots | Antioxidant activity assay | Equal volume ratio (1:1) | 70% |
| Chen et al. [49] | *Curcuma longa L.* (Turmeric) | Ionic liquid UAE-hydrodistillation (IL-U-HD) | Liquid–material ratio of 12:1 | 22% |
| Lee et al. [53] | *Phedimus aizoon* | GC-MS and HPLC chromatographic analyses | – | 24–28% |

## 4. Evaluation of UAE Extracts

### 4.1. Response Surface Methodology and Optimization of UAE

The ideal conditions for extracting the total phenolic content (TPC) from V. Sinaiticus were found in 20 experimental runs by testing independent variables including sonication time, solvent-to-solute ratio, and extraction temperature in the UAE. A second-order polynomial equation was found for the response variables as follows

$$Y_n = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12} x_2^2 + \beta_{13} x_3^2 + \beta_{23} x_3^2 \quad \ldots. \ (1)$$

where $Y_n$ (TPC) is represented by the variables $\beta_0, \beta_i, \beta_{ii}$ and $\beta_{ij}$. These are the intercept, linear regression coefficient for the $i$-the component, quadric, and interaction effect term, and the independent variables are coded as $X_i$ and $X_j$ .The number of variables being examined is denoted by $k$ [45].

### 4.2. Total Phenolic Compounds

The total phenolic content was calculated using the Folin-Coalter procedure with minimal modifications [56]. In a 15 mL centrifuge tube, 5 mL of extract and 5 mL of 80% methanol were mixed together. After that, the tubes were centrifuged for 20 minutes at 4000 rpm at 4–16KS, Germany. For analysis, 3000 L of deionized water, 100 L of Folin Coalter reagent, and 100 L of a standard solution or suitably diluted sample (10−100 g/mL) were mixed together and vortexed. After 10 minutes of room temperature incubation, 100 L of a 20% sodium carbonate solution was added right away, stirred, and allowed to sit at room temperature for two hours in the dark. The absorbance of the combination at 765 nm was then measured using a microplate reader (Biotech Synergy 2 Microplate reader, USA). Using milligrams of gallic acid as the reference, the total phenolic contents of the samples were represented as milligrams of gallic acid per 100 milliliters.

### 4.3. Total Flavonoids Content (TFC)

TFC was assessed using Zhi's hen et al.'s methodology [57]. First, 2.5 mL of distilled water, 0.15 mL of 5% sodium nitrite, and 0.5 mL of the extract were mixed together. After 6 minutes of standing time, 0.3 mL of 10% m/V aluminum chloride was added to the mixture and properly mixed. This was followed by the addition of 0.55 mL of distilled water and 1 mL of 1.0 M sodium hydroxide. After that, the mixture was vortexed and allowed to stand for fifteen minutes. Utilizing a UV-Vis spectrophotometer (Opti Zen 2120UV; Metasys Co., Ltd., Daejeon, Republic of Korea), the concentration was lastly measured at 510 nm. For quantification, a calibration curve for catechin was created, and the results were given as (mg CE/g DW) dry extract of the sample.

### 4.4. Total Polyphenol Content

The Folin-Coalter approach was used to calculate TPC calorimetrically [58]. 2.5 mL of 10% Folin-Coalter reagent (FCR) was combined with 0.2 mL of the extract to create the solution. Two milliliters of a 7.5% sodium carbonate solution containing 75 g/mL was then added. After 10 minutes of heating to between 50 and °C, the sample was let to cool. A Spectra i3x plate reader (Molecular Devices, LLC., Seoul, Republic of Korea) was used to measure the absorbance at 750 nm. Gallic acid standard was used to create a calibration curve, and the results were reported in mg GAE/g dew.

### 4.5. DPPH Scavenging Assay

The ability to scavenge free radicals while interacting with a stable DPPH free radical was used by Ciconine, Iadanza's, and Vikas [59] to evaluate antioxidant activity.

Using Equation (2), antioxidant activity was computed as a percentage of radical scavenging.

$$\%\ \text{radical scavenging percentage} = \frac{A0 - A1}{A0} \times 100 \qquad \ldots. \qquad (2)$$

The absorbance of the control reaction, which contains all reagents except the test substance [$t$=0 min], is denoted by A0. ($t$=30 min) Al = absorption of test extract solution. After 30 minutes of incubation, the light absorption at room temperature was measured at 517 nm. With comparable AOA reported as $\mu$M Trolox per g DW, the DPPH radical scavenging activity was shown as a function of Trolox concentration.

### 4.6. ABTS radical cation decolorization assay

The extracts' ability to scavenge radicals against radical cations (ABTS, -++.) was calculated using a previously published method with minor adjustments [60]. In terms of $\mu$M TE/g DW, the results were presented.

### 4.7. Ferric reducing antioxidant power assay (FRAP)

The FRAP assay was performed in accordance with Benzie and Strain's protocol [61]. Every day, the FRAP reagent was made from scratch and heated to 37 °C before use. Following four minutes of incubation at 37 °C, the absorbance of the reaction mixture was measured at 593 nm. $\mu$MTE/g DW was used to express the results.

### 4.8. Thermogravimetric Analysis

The thermogravimetric analysis (TGA) of the 70% ethanol extract of S. japonica UAE was carried out using an SDT Q600 (V20.9 Build 20) and the nano emulsion (ENE). A sample of about 20 milligrams was quantified and carefully packed in aluminum containers. The samples were flushed with nitrogen at a rate of 30 mL/min while being raised from 30-40°C

to 600-°C at a rate of 10-°C/min. A metal container that was empty served as the reference [62]. The impact of ethanol on stability was assessed by comparing the sample with the UAE 100% water extract nano emulsion (WNE).

### 4.9. Colorimetric Analysis

A colorimeter was used to assess the extracts' color [63]. The equation that was used to determine the overall chromaticity difference ($E$) used the values for $L^*$ (lightness), $a^*$ (redgreen), and $b^*$ (yellow-blue):

$$\Delta E = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{\frac{1}{2}} \quad \ldots\ldots\ldots \quad (3)$$

The values of $\Delta L, \Delta a$ , and $\Delta b$ were calculated by subtracting the standard color parameters from the corresponding, $L^*$, $a^*$, and $b^*$ values. The square root of the sum of the squared differences in, $L^*$, $a^*$, and $b^*$. was then used to compute the total chromaticity difference ($\Delta E$). Whiteboard values were calibrated as $L^* = 89.03; a^* = 0.35; b^* = 3.42$.

### 4.10. X-Ray Diffraction

A German Bruker D8 Advance x-ray diffractometer (XRD) was used to examine the crystal structures of several dry samples. Prior to testing, the samples were flattened and positioned in the middle. The scanning range for $2\theta$ was established at a rate of 5° per minute and was set to $5° - 40°$. To determine the crystal structure, the diffraction patterns were gathered and examined [64].

### 4.11. Attenuated Total Reflectance-Fourier Transform Infrared

An FTIR spectrometer (Nicolet iS50, Thermon Electron, USA) fitted with a diamond crystal attenuated total reflection (ATR) accessory was used to acquire the Fourier transform infrared (FTIR) spectra of dry materials. With a resolution of 4, cm-1, and a predetermined number of scans of 16, the spectra were obtained between 4000 and 500 cm-1 [65].

### 4.12. Confocal Laser Scanning Microscopy

Using a confocal laser scanning microscope (CLSM) (Leica TCS SP5, Germany), the emulsions' morphology was described. The micromorphology of the emulsion was examined using CLSM. At a temperature of 25 °C, 10 L of the emulsion was specifically placed on a microscope slide, covered with a coverslip, and examined with a 100× oil immersion objective lens. Every picture was taken with a scanning frequency of 200 Hz and a scanning density of 1024 × 1024 [66].

## 5. Conclusion

Ultrasonic-assisted extraction (UAE) represents a significant advancement in the field of green extraction technologies, offering an efficient, cost-effective, and environmentally friendly alternative to conventional methods. By harnessing acoustic cavitation, UAE enhances mass transfer and disrupts plant cell matrices, resulting in improved extraction yields of phenolics, flavonoids, and other bioactive with reduced solvent usage and shorter extraction times. The application of statistical optimization techniques such as response surface methodology (RSM) has further refined UAE parameters, enabling targeted recovery of specific compounds. Analytical evaluations, including DPPH, ABTS, FRAP assays, and structural analyses (HPLC, NMR, FTIR, XRD), affirm the superior antioxidant capacity and stability of UAE-derived extracts. Despite its many advantages, challenges such as equipment scale-up, standardization, and compound degradation under high-intensity sonication remain. Future research should prioritize the integration of green solvents, real-time monitoring technologies, and artificial intelligence-based modeling to further optimize UAE for industrial applications. Overall, UAE holds tremendous promise for sustainable and scalable extraction of bioactive compounds from medicinal plants, supporting its broad utility in functional food, pharmaceutical, and cosmetic industries.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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