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# Ultrafine comminution-assisted ultrasonic-microwave synergistic extraction of *Pueraria mirifica* (Kudzu flower and root) flavonoids

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ABSTRACT

Extracts of the *Pueraria mirifica* (Kudzu) plant have several significant human health-promoting benefits. This study utilized orthogonal tests to evaluate the effects of differential ultrasonic power, microwave, and time on the rate of flavonoid extraction from Kudzu samples. Ultrafine processing resulted in finer powder microstructures (SEM) with high solubility. The smallest D50 measurements of ultrafine Kudzu flower and root particles were 11.7 ± 0.004b and 14.3 ± 0.013c μm, respectively. Increasing ultrasonic power from 200 to 600 W yielded increased flavonoids. Increased microwave power from 200 to 800 W also yielded increased flavonoid extract. We found that the best combination factor was A3B2C3 (A-ultrasonic power, B- time, and C-microwave power), showing that flavonoid extraction rate was primarily influenced by microwave power, followed by ultrasonic time and ultrasonic power. Conclusively, ultrafine pulverization increased the flavonoid extraction rate from Kudzu powder particles. Also, scanning electron microscopy results showed that the finer particles had increased solubility.

## 1. Introduction

A tubular Chinese herb, *Pueraria mirifica*-is a common leguminous plant with a quick growth rate and is locally known as Kudzu in most Asian nations [1]; [2]. There are about seventeen (17) species of Kudzu worldwide, all native to China. The most widespread and resourceful Kudzu species are wild [3]. Kudzu is a fantastic good ground cover, an excellent source of fodder for wildlife, a good source of fibre, and nutrient-rich food for humans. Its tuber and leaves contain significant phytochemicals and extracts that have historically been used in medicine and nutrition, such as puerarin, daidzein, daidzin, iris, and irisin [4]; [2]. These phytochemicals have benefits that include improved immunity, blood lipid control, hypoglycemia, anti-arrhythmia, anti-hepatotoxic, anti-oxidant, anti-mutagenic, anti-myocardial ischemia, and anti-dipsotropic [5]; [6]. In studies with alcohol-induced inflammatory conditions, researchers elucidated several plant-derived additives capable of lessening the impact of congeners [7]; Kudzu showed the best congener-impact lessening results due to its flavonoids contents (amongst other health benefits). Kudzu roots reduced hangover symptoms in mice with acute alcohol poisoning. They increased acetaldehyde's removal and metabolism in the blood and liver, according to studies with dried flower buds of wild Kudzu [8–10].

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Although it is well known that plant-based diets contain nutrients and ingredients that are good for health promotion, there is a need for either minimal or extensive processing due to the internalization and low bioavailability of these important nutrients [11–15]. Kudzu's importance is growing due to its positive pharmacokinetic and pharmacodynamic interactions and effects. However, the development of its full economic advantages have been significantly constrained due to the absence of modern processing technology and limited bioaccessibility [16–18]. Using efficient modern processing or extraction techniques can yield a high quantity of food-rich bioactive components for both industrial applications and higher health promotion. Recent studies are utilising emerging extraction technologies like ultrasonic applications [19] and microwave [20] with effective results. This study combined these two applications for the extraction of flavonoids from Kudzu samples. Ultra-fine pulverization creates tiny particles with outstanding qualities like high solubility and dispersibility [21]; [22,23]. Ultrasonic power and microwave-assisted extraction methods have been used by several researchers due to their reduced time, minimal solvent consumption, higher extraction rates, and greater environmental protection [24,25]. Micronized food particles with greater specific surface area, better bioactivity and absorption rates, sensory properties, and improved surface charge and viscosity could enhance the bioavailability and health-promoting effects of food bioactive substances. This study aims to utilize orthogonal tests to evaluate the effects of differential ultrasonic power, microwave, and time on the rate of flavonoid extraction from Kudzu samples.

## 2. Materials and methods

### 2.1. Experimental consumables and equipment

#### 2.1.1. Experimental reagents

The lists of instruments and reagents are presented in the supplementary file; see Supplementary Tables 1 and 2

### 2.2. Preparation of Kudzu roots and flower

*Pueraria mirifica* (Kudzu) plants were obtained from Wuyi Mountain and Zhangjiajie. Fresh Kudzu roots were washed, chopped into 12 cm thick pieces (not sliced), and dried in hot air at 60 °C to facilitate easy grinding after being cleaned of dust and other pollutants. To create ultrafine particles, dried Kudzu root and petal samples were first ground into a coarse powder and then refined for an additional 15 min. Standard 100, 200, and 300 mesh sieves were used to screen and bag the resulting powder. The powders were stored in sealed bags at 0–4 °C, free from moisture and light, before particle size-biased physicochemical examinations.

### 2.3. Physicochemical analysis of ultrafine Kudzu powder

A laser particle size analyzer was used to assess the sizes and shapes of Kudzu power of various meshes [26]; after this, maps of the cumulative distribution and particle size frequency distribution were created depending on volume.

### 2.4. Ultrafine Kudzu powder surface morphology examinations

Each ultrafine Kudzu powder sample (flowers and roots) was examined in three portions. According to the procedures previously outlined [27], they were uniformly distributed in the scanning electron microscopy (SEM) sample stage. After the gold spray coating of the particles and setting the accelerating voltage at 3 kV A, at a distance of 12.5 mm, and at 500× and 1000× magnification, photographs of the structure and surface morphology of the Kudzu powders were seen and recorded.

### 2.5. Determination of the resting angle of ultrafine Kudzu powder

Measuring the resting angle provides an intuitive way to determine the relative degrees of freedom in flow between powder particles. This made it possible to select the best mesh size for fine powder [28]. The glass funnel was suspended vertically on the iron bracket. Next, 100, 200, and 300 mesh-sized ultrafine Kudzu powder were funnelled through by fixed/weighed amounts, falling vertically to the bottom reception table. When the cones are created, formula 1 was used to determine the ultrafine powder's resting angle:

$$\theta = \arctan H/R \quad (1)$$

Key: θ- Rest corner; R- Cone radius; H- The vertical distance between the bottom of the triangular glass funnel and the glass plate.

### 2.6. Dissolution performance of ultrafine Kudzu powder

Precisely 1 g (anhydrous, dry basis) of powder samples were placed in graduated centrifuge tubes- 50 ml of pure water was added to the tubes. In graded centrifuge-lidded tubes, 1 g (anhydrous, dry basis) of powder samples were introduced. After that, 50 ml of distilled water was added to the tubes. For 30 min, the tubes were heated on a shaker at three different temperatures (60, 80, and 100 °C) to prevent precipitation. After centrifuging the tubes for 20 min at 3000 rpm, the supernatant was evaporated in a water bath until a constant weight [m (g)] was obtained at 105 °C. The solubility of Kudzu powder was determined at various temperatures using

formula 2:

$$S / \% = m \times 100 \quad (2)$$

### 2.7. Flavonoid extraction univariate test

Ultrafine Kudzu powder was weighed, 60 % ethanol solution was added, ultrasonic microwave join extraction was carried out, tubes were centrifuged at 4000 rpm for 10 min, the mixture was filtered, and total flavonoids were determined using the supernatants [29].

#### 2.7.1. Flavonoid extraction univariate test

The association between ultrasonic power and the flavonoid extraction rate was analyzed. Cells are more effectively ruptured by ultrasonic cavitation than microwaves, which employ mass transfer and unequal heat transfer [30]. At a temperature of 50 °C, a liquid-to-material ratio of 20:1, an ultrasonic processing duration of 40 min, a microwave power of 400 W, and other conditions, the impact of ultrasonic pulverization on the extraction rate of flavonoids was clarified.

#### 2.7.2. Effect of ultrasound time on the flavonoid extraction rate

The energy consumption of flavonoids and extraction rate are correlated. Insufficient extraction time results in an inadequate extraction rate, yet, prolonged extraction time has the same effect as prolonged microwave or ultrasonic action time-degraded flavonoid with less bioactivity impact. As the extraction agent, we used a 60 % ethanol solution and 10, 20, 30, 40, and 50 min for the ultrasonic duration. Using a liquid-to-material ratio of 20:1 (ml/g), 400 W of ultrasonic power, and 400 W of microwave power, we investigated the impact of ultrasonic duration on flavonoid extraction rates.

### 2.8. Effect of microwave power on flavonoid extraction rate

#### 2.8.1. Orthogonal test of flavonoid extraction from kudzu powder

The orthogonal tests were utilized with the univariate data to clarify the effects of microwave, ultrasonic power, time factors and flavonoid extraction rate under ideal processing circumstances. The orthogonal test's specific design is presented in the Supplementary file (see Supplementary Table 3). This test design allows for the evaluation of different treatment parameters during sample extraction [25]. Results suggest the best factor combinations that will yield the highest extraction rate of samples.

#### 2.8.2. Rutin standard curve for kudzu powder

Weigh 5 g of the Kudzu sample and add 60 % ethanol aqueous solution in a material-to-liquid ratio of 1:10 (g/ml) for microwave or ultrasonic extraction. Collect the resulting solution and measure its flavonoid content six times. Calculate the average measurement value (three closest results) after removing the maximum and minimum values. Using the rutin standard as the control substance, the $NaNO_2$–$Al(NO)_3$ colourimetric method [30] was used to determine the flavonoid content of ultrafine Kudzu powder. A 10 ml volumetric flask was filled with 0, 1.0, 2.0, 3.0, 4.0, and 5.0 ml of the rutin standard solution to obtain the rutin standard (0.2 mg/ml). Precise amounts of 5 % sodium nitrite and 75 % ethanol were applied to 5 ml of rutin standard and allowed to sit for 6 min. After that, 4 % sodium hydroxide 4.0 ml was added and left for another 6 min, and 75 % ethanol was used to set the volume to 10 ml, shaken well, and stood for 15 min. The solution was then used as a reference to determine the absorbance at a wavelength of 510 nm. The linear regression equation between absorbance (A) and rutin mass fraction (C, mg/ml) was obtained according to the measured data: Y = 1.706x+0.012 (R2). = 0.9922) (see Supplementary Fig. 1 in the supplementary file). The sample solutions were measured precisely in 1 ml and 10 ml volumetric flasks. The process was the same for drawing curves using the standard method. The total amount of flavonoids may be determined using its absorbance and regression equation, and the flavonoid yield can be determined using formula 3:

$$\text{Flavonoid yield (mg / g)} = \frac{\text{Total flavonoid in the extracts (mg)}}{\text{Ultrafine powder mass (g)}} \quad (3)$$

### 2.9. Ultrasound and microwave machine calibration

The temperature protection set point of the machines must be at least 5 °C higher than the room temperature or sample temperature. The machine was started after inserting the amplitude converter into the liquid (empty) and was preheated for 10 min. Before sample measurements, an oilstone or file was used to flatten the end of the horn. This prevents cavitation, corrosion, and fuzzing of the horn end, which may affect the experimental results.

### 2.10. Statistical analysis of data

Wield Origin 8.5 was used to analyze the triplicate data using the "average value ± standard deviation" method. When the *p*-value is between 0.05 and 0.01, it means that there is a significant difference in average numerical results. All results were averages of triplicate measurements.

## 3. Results and discussions

### 3.1. Effect of ultrafine pulverization Kudzu powder properties

#### 3.1.1. Effect of feed particle size on particle size

The different mesh size feedings resulted in noticeable variances in the diameters of the ultrafine Kudzu particles. The smallest diameters for the Kudzu flower and root particles were obtained using mesh size 300 for D10, D50, and D90 measurements. The smallest particle sizes during D50 measurements for ultrafine Kudzu flower and root were 11.7 ± 0.004b and 14.3 ± 0.013c μm, respectively. In contrast, the maximum particle sizes at D50 measurements for ultrafine Kudzu flower and root particles were 20.11 ± 0.004a μm (200 mesh) and 222.3 ± 0.001a μm (100 mesh), respectively. Kudzu powder particles sieved with 300 meshes had the highest concentrations and smallest particle size distribution (see the supplementary file-Supplementary Fig. 2). The particle size distributions of the other groups were wide and had poor concentrations. Moreover, the size distribution of the ultrafine Kudzu particles showed consistent and substantial decreasing trends at the D90 measurement (See Table 1). In contrast, the trend at D50 measurement shows that ultrafine Kudzu powder is more likely to clump together due to mechanical force and van der Waals forces when the particles were fed at a particle mesh size or when the powder particles were ground to a certain level. The size distribution data and phenomenon collaborate with the scanning electron microscopy (SEM) data.

### 3.2. Scanning electron microscopy (SEM) analysis of Kudzu powders

Kudzu ultrafine powder particles' microstructure and size distribution are depicted in Fig. 1. Varying Kudzu powder sizes were seen using SEM at the 500× magnification level (Fig. 1A). Due to the friction and mechanical pressure present in the ultrafine pulverizer, large Kudzu particles were broken up and sorted into smaller particle sizes of various shapes-ranging from irregular to spherical. The varied particle sizes were induced by the various mesh sizes; when the powder was sorted, the rod-like and irregular particles decreased, and finer particles emerged. At 1000× scanning electron magnification (SEM) mode, there were increased mesh size screens, loosened, broken, and fractured ultrafine Kudzu powder particles. These particles were seen to have more rounded edges and rough surfaces, indicating larger specific surface areas of the resulting ultrafine kudzu powder (see Fig. 1B). This has significant implications for how its active component functions [31,32]. At the same time, finer particle fragments conductively formed amorphous regions-aiding easier dissolution rate of active substances during hydrolysis. Like cells' pectin content, other bioactive substances (flavonoids, phenolic acids, and carotenoids) are primarily bound by covalent bonds to the cell wall. This makes it difficult for them to dissolve by certain solvents.

At 1000× magnification mode also showed that with a higher mesh number, the larger linear fibres of ultrafine Kudzu powder reduced. There was more roughness on the particles' surfaces; however, with a mesh number higher than 200, the morphology of ultrafine Kudzu powder had little changes, and the agglomeration phenomenon was more noticeable. The above data are consistent with the extraction rate-there were no significant changes with increasing magnification (above 500×). Also, the observable differences between ultrafine Kudzu flower and root power could be due to their different structure; the Kudzu flower majorly contains starch and about 12 % flavonoid. Even though Kudzu powder particles contain many hydroxyl groups, their hydrophilicity is high, making it challenging to clump [33]. On the other hand, Kudzu roots are predominantly cellulose, lignin, and pectins-more of carboxyl groups, high propensity to clump. When the 200 and 300 meshes were utilized for particle size sorting, the electrostatic adsorption during ultrafine processing produced little to no morphological variations [34].

### 3.3. Determination of the resting angle of ultrafine powders

From Fig. 2, it can be inferred that the fluidity of ultrafine Kudzu powder resting angles showed a declining trend. A powder's fluidity density and resting angle are strongly associated; the smaller the resting angle, the better the powder's fluidity [35]. The degree of crushing, decreased powder size, increased specific surface area, and increased molecular force between powder particles are the variables that influenced the resting angles of the powder samples in this study. These particles moved under gravity more readily with better fluidity, and there were significant differences among the mesh groups ($p < 0.05$) used to produce this result. In contrast, no

**Table 1**
Effect of different feed particle sizes on particle size.

| Sample/mesh feed size (μm) | Granularity ( μm ) | | |
|---|---|---|---|
| | D10 | D50 | D90 |
| Kudzu flower 100 | 2.42 ± 0.004a | 17.5 ± 0.002a | 63.7 ± 0.011a |
| Kudzu flower 200 | 2.81 ± 0.003a | 20.11 ± 0.004a | 55.2 ± 0.012b |
| Kudzu flower 300 | 1.88 ± 0.004b | 11.7 ± 0.004b | 37.2 ± 0.004c |
| Kudzu root 100 | 51.8 ± 0.015a | 222.3 ± 0.001a | 472.2 ± 0.001a |
| Kudzu root 200 | 9.14 ± 0.004b | 43 ± 0.004b | 96.8 ± 0.007b |
| Kudzu root 300 | 3.51 ± 0.011c | 14.3 ± 0.013c | 40.8 ± 0.004c |

There are no significant differences amongst values of similar alphabets at a 95 % ($p < 0.05$) confidence level. There are significant differences between values of dissimilar alphabets at a 95 % confidence level

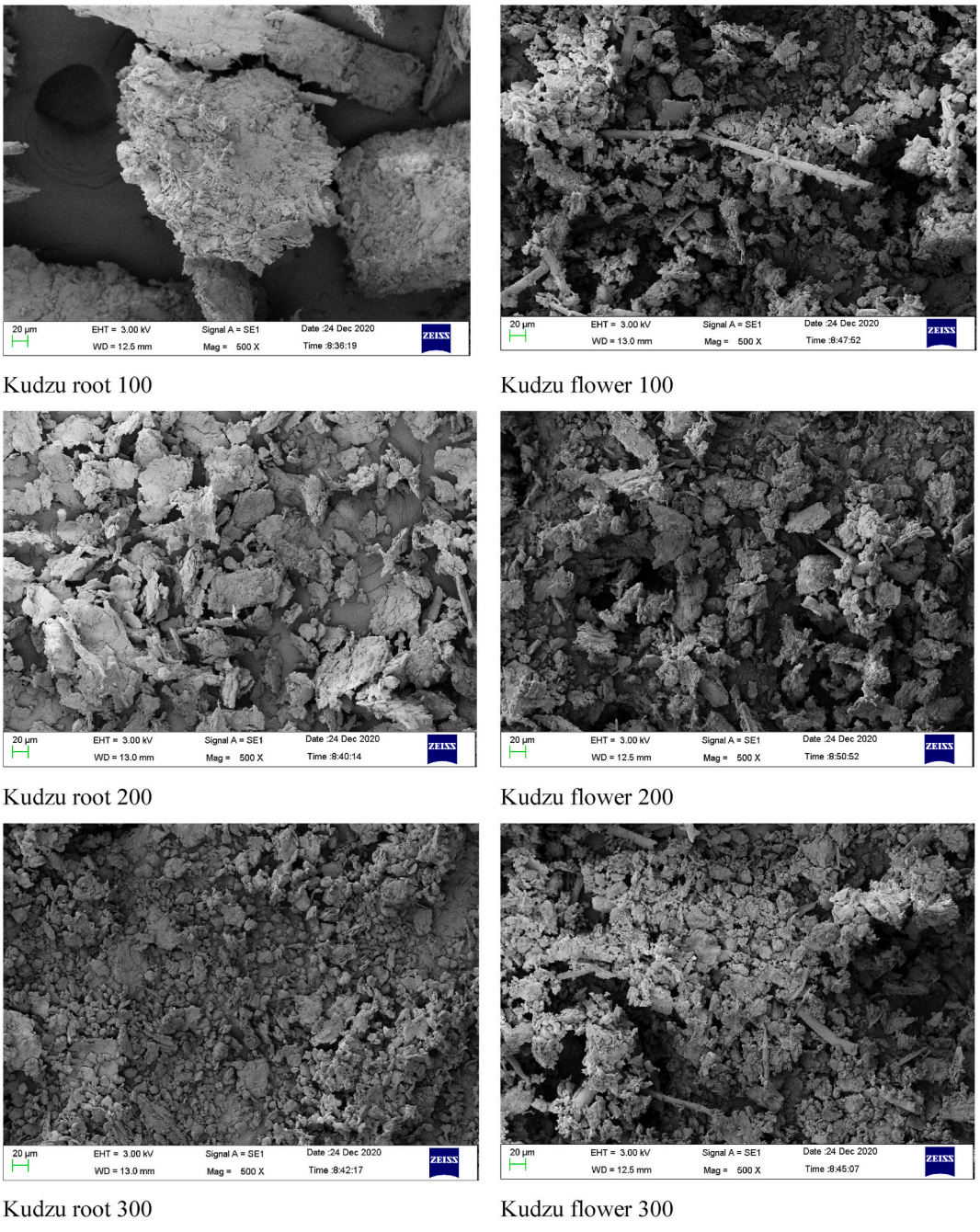
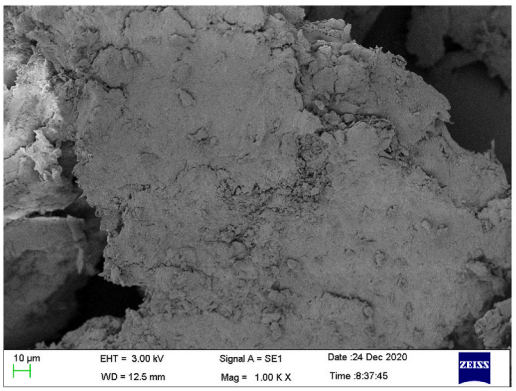



**Fig. 1.** A: Scanning electron microscopy (SEM) results of Kudzu powders (500×). B: Scanning electron microscopy (SEM) results of Kudzu powders (1000×).

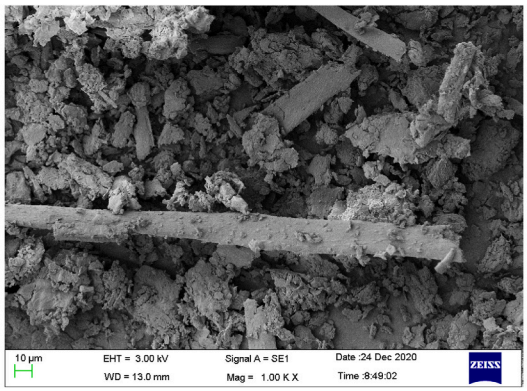
significant differences ($p > 0.05$) in resting angles between powder sizes with mesh sizes 200 and 300 due to the presence of cellulose, lignin, and pectin-like compounds. This improved their fluidity and was consistent with the results of the particle size determination [36]. This data is consistent with the SEM data and reveals that Kudzu root powder clumped bigger particles better.

### *3.4. Effect of ultrafine pulverization on Kudzu Powder's solubility*

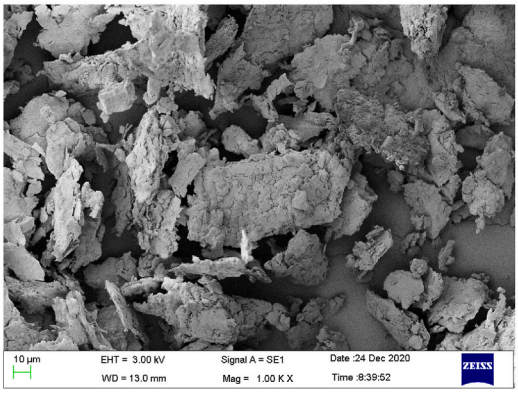
Fig. 2 also shows that enhanced pulverization increased the degree of Kudzu powder solubility; also, there were no significant differences between the solubilities of ultrafine Kudzu root and flower powders (at 200 and 300 meshes). Invariably, these results show



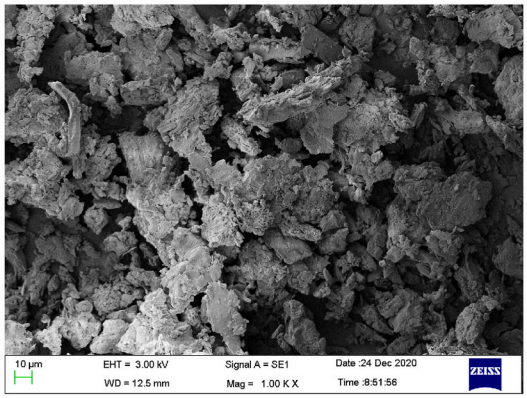

Kudzu root 100



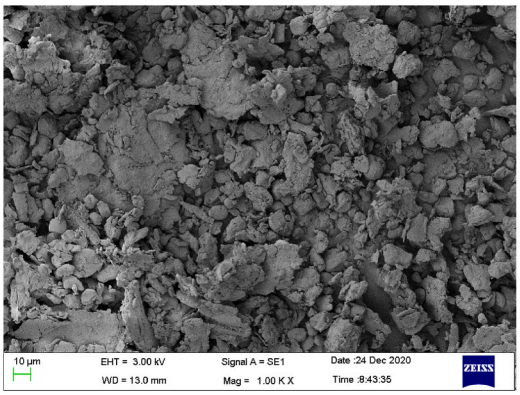

Kudzu flower 100



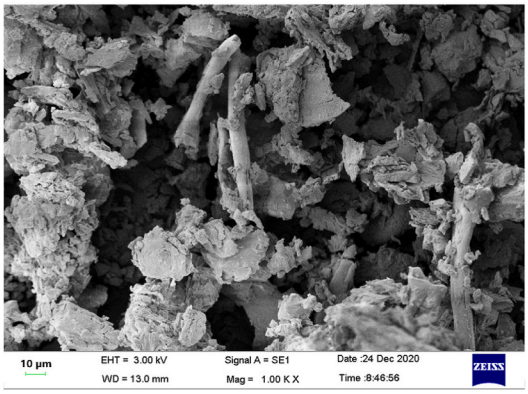

Kudzu root 200




Kudzu flower 200




Kudzu root 300




Kudzu flower 300

**Fig. 1.** (*continued*).

that increased pulverization intensity degraded the cellulose and hemicellulose contents in Kudzu powder and increased their solubilities. However, when the temperature increased, the soluble substances became insoluble, leaving no discernible variation in the solubilities of the ultrafine Kudzu powder particles. These solubility results were consistent with those of Zhang and his team (M [37]. Observably, particles from 300 mesh of the ultrafine Kudzu root and flower powders were used for further studies.

### *3.5. Combined ultrasonic and microwave extraction process analysis*

#### *3.5.1. Effect of ultrasonic power on flavonoid extraction rate from kudzu roots*

We evaluated the effect of ultrasonic extraction and flavonoid concentrations on Kudzu powders. Fig. 3a shows that the extracted flavonoid rate initially increased but declined with increasing ultrasonic power. When ultrasonic power was between 200 and 600 W,

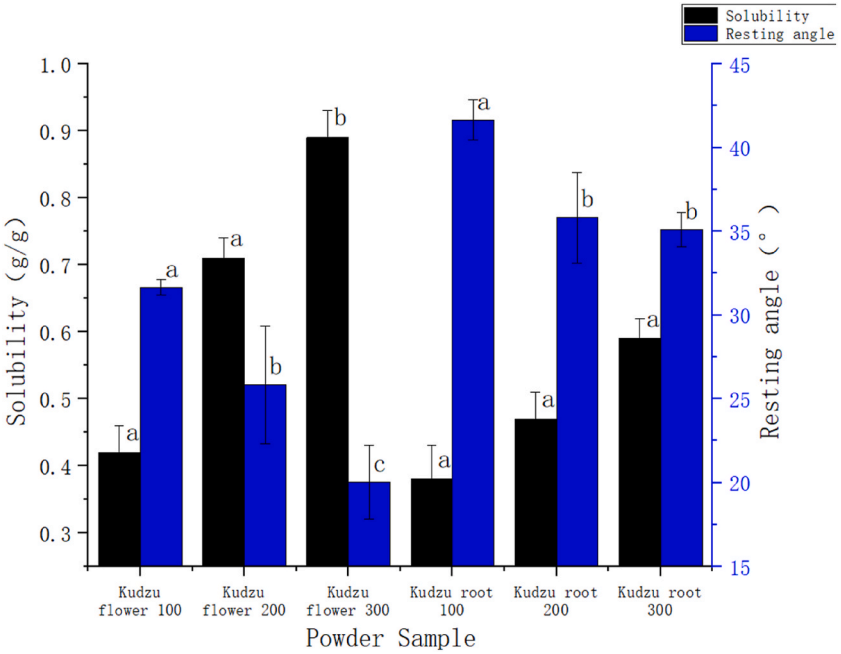



**Fig. 2.** Physicochemical properties of ultrafine Kuduz powders.

there was a positive association between the two variables; however, once power exceeded 600 W, there was a negative correlation. The highest extraction rate was 4.70 % (at 600 W ultrasonic power). In principle, higher ultrasonic power disrupted the cell wall structures – and the release of essential bioactive components from plant cells. However, increased ultrasonic power, increased intensity, and liquid pressure, which in turn increased the energy transfer process and decreased extraction rate [38]. Hence, the optimal ultrasonic power for flavonoid extraction was 600 W. Another study that combined ultrasonic extraction method and deep eutectic solvents (DESs) had higher amino acid and total individual organic acid values compared to the control that used only ethanol [39].

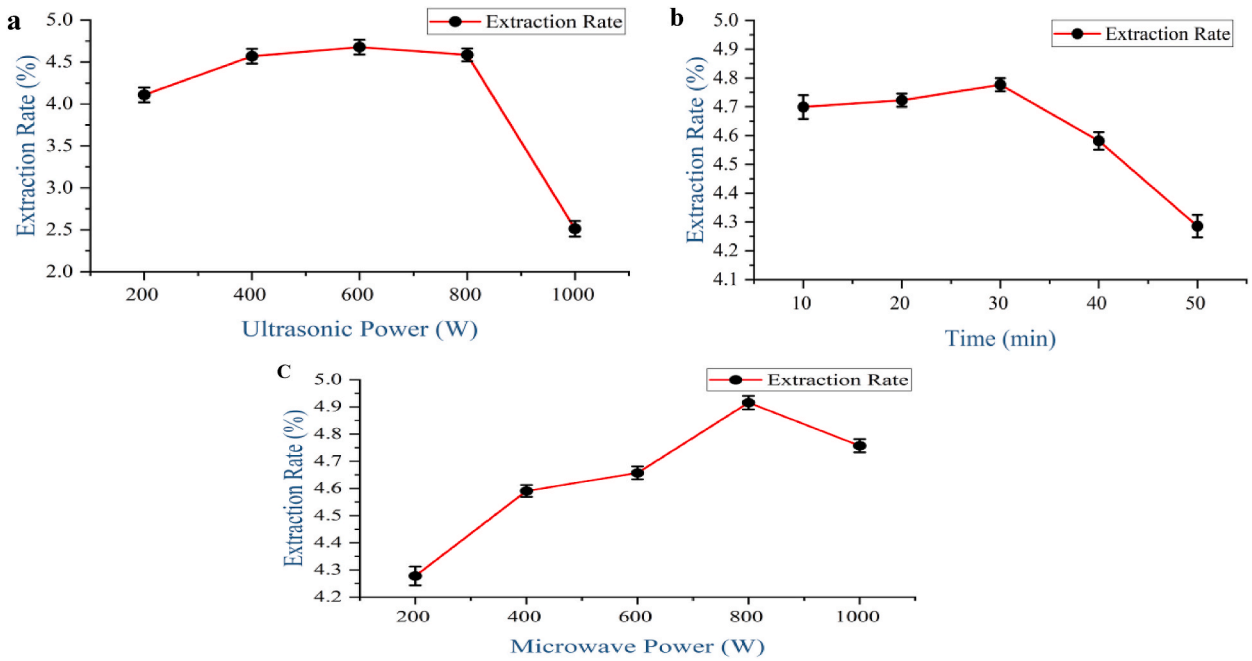



**Fig. 3. Effect of combined ultrasonic and microwave extraction process analysis.** (a) Effect of ultrasonic power (W) on the flavonoid extraction rate (b) Effect of ultrasonic time (min) on the flavonoid extraction rate (c) Effect of microwave power (W) on the flavonoid extraction rate.

### 3.5.2. Effect of extraction time on the extraction rate of Pueraria flavonoids

The extraction rate is a factor of the length of extraction time and the energy expended. This study kept other parameters, such as the ultrasonic power at 400 W, the ethanol content at 60 %, and the liquid-to-material ratio at 20:1, while analyzing the flavonoid extraction rate and ultrasonic power across graduated times of 10, 20, 30, 40, and 50 min. The results demonstrated that shorter extraction times resulted in insufficient flavonoid extraction, but longer extraction times (and greater ultrasonic power) resulted in flavonoid decomposition, which lowered their quality. In another study, ultrasonic treatment power of 400 W maintained for 15 min yielded improved water vapour permeability and tensile strength of soybean aqueous extract-based composite film [19]. The film material showed promising storage properties for certain food items. The flavonoid extraction rate in this study increased substantially as ultrasonic time was increased between 10 and 30 min; however, the yield decreased after that point (see Fig. 3b). The maximum extraction rate was 4.78 % at 30 min; lengthy extraction time resulted in a decomposed flavonoid structure. This outcome supported Zhang and his team's findings (M [40].

### 3.5.3. Effect of microwave power on the extraction rate of Pueraria flavonoids

Additionally, the correlation between flavonoid extraction rate and microwave power was studied. Other parameters were consistent as in the previous test; ultrasonic power 400 W, 60 % ethanol, liquid-to-material ratio 20:1, 40 min. However, we varied the microwave powers (200, 400, 600, 800, and 1000 W) and evaluated their effects on the flavonoid extraction rate. In this study, it can be inferred that as the microwave power gradually increased (200–800 W), flavonoid extraction initially increased and decreased at the 800 W point (see Fig. 3c). The highest extraction rate was 4.92 % at microwave power at 800 W (Temperature 55 °C). Increased microwave power enhances the molecular interactions between the electromagnetic field and the samples-leading to efficient extraction according to Ref. [41]. This team also observed that increased total carotenoid and chlorophyll contents of dried *Inula viscosa* (L.) samples (at 100 and 180 Watts) were higher than the extraction rate at 300 Watts [41]. Another team reported a higher extraction rate and enhanced functional properties of pectin polysaccharide from jackfruit waste after using combined pulsed electric field treatment and microwave-assisted extraction [20].

## 3.6. Analysis of orthogonal test results

The orthogonal test findings are shown in Table 2; the analytical range was RC > R A > RB. Microwave power, followed by ultrasonic power and then ultrasonic time, can be rated as the main variables influencing the flavonoid extraction from *Pueraria mirifica.* We graded the orthogonal test from Table 2 as ultrasonic power k3 > k2> k1; microwave power k3 >k2 > k1; and ultrasound time k2 > k1> k3. By selecting the best sets of the three factors—ultrasonic power k3, microwave power k3, and ultrasound time k2—we were able to create the best combinations. Therefore, the best combination is A3B2C3 (A-ultrasonic power; B- time; and C- microwave power). The extraction rate of flavonoids from Kudzu roots is largely influenced by microwave power, followed by ultrasonic time and ultrasonic power. Results from the flavonoid extraction process from *Pueraria mirifica* (Kudzu) roots were obtained by combining ultrasonic and microwave powers (at 850 and 650 W) for 30 min. These combined parameters yielded three parallel corresponding flavonoid extraction rates of 4.83, 4.87, and 4.89 % (averaging 4.86 % extraction rates). Flavonoid extraction levels from Kudzu roots were high, showing that these orthogonal results are reproducible and feasible. The results of the treatment for the ultrafine Kudzu powder residues are shown in Fig. 4A. A similar flavonoid extraction optimization study from *Inula helenium* resulted in increased yield [25].

Although there was minimal to no visible damage due to the ultrasonic treatments, the clumping trend was greatly reduced. The increased ultrasonic shear stress reduced the particles' clumping characteristics but did not affect their structure. This could be attributed to the high starchy content of Kudzu flowers, which allowed particles to reaggregate into dense insoluble starch molecular microcrystalline bundles [42]. Moreover, a higher ultrasonic power resulted in a reduced rate of flavonoid extraction. Increased microwave treatment significantly reduced the ability of big Kudzu flower particles to bind hydroxyl electrostatically, producing a

**Table 2**
Orthogonal experimental design and results.

| Sequence | A | B | C | Extraction rate (%) |
|---|---|---|---|---|
| | Ultrasonic power (W) | Time (minutes) | Microwave power (W) | |
| 1 | 550 | 25 | 750 | 4.74 ± 0.72 |
| 2 | 550 | 30 | 850 | 4.64 ± 0.35 |
| 3 | 550 | 35 | 800 | 4.78 ± 0.44 |
| 4 | 600 | 25 | 800 | 4.77 ± 0.41 |
| 5 | 600 | 30 | 750 | 4.85 ± 0.40 |
| 6 | 600 | 35 | 850 | 4.63 ± 0.36 |
| 7 | 650 | 25 | 850 | 4.73 ± 0.56 |
| 8 | 650 | 30 | 800 | 4.80 ± 0.63 |
| 9 | 650 | 35 | 750 | 4.77 ± 0.39 |
| K1 | 4.72 | 4.75 | 4.72 | |
| K2 | 4.75 | 4.76 | 4.73 | |
| K3 | 4.77 | 4.73 | 4.79 | |
| R | 0.05 | 0.03 | 0.07 | |

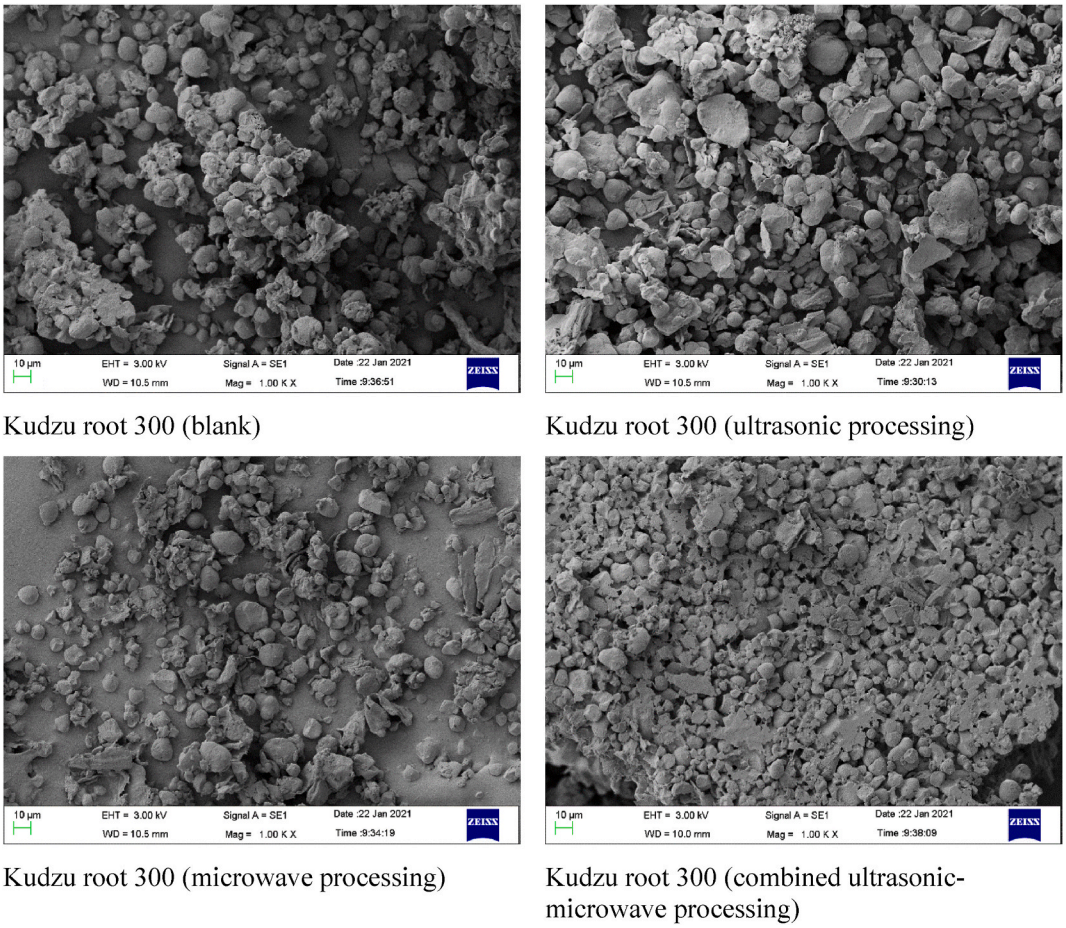



**Fig. 4.** A: Effect of ultrasonic power and microwave on total flavonoid content of Kudzu root powder. B: Effect of ultrasonic power and microwave on total flavonoid content of Kudzu flower powder.

finer, spherically dispersed Kudzu flower powder [43,44]. Due to the high levels of fibre and lignin and the high strength of the hydroxyl electrostatic adsorption capacity of the Kudzu flower, Fig. 4B shows that ultrasonic treatment on large Kudzu flower particles did not considerably decrease [43,45,46]. Although their clumping phenomena were still considered due to the combined ultrasonic and microwave treatment, large ultrafine Kudzu powder was also significantly destroyed by high microwave power. The resulting particles were more spherical, clump-capable, and finer. Another team that combined microwave technology and ultrasound pre-treatment to dry *Inula viscosa* (L.) leaves reported that its antioxidant and qualitative qualities were not compromised [41].

## 4. Conclusions

The effects of differential ultrasonic power, microwave, and time on the rate of flavonoid extraction from Kudzu samples were evaluated using the orthogonal test. Innovative food processing methods like ultrafine pulverization can be used in creating food products with increased nutritional value; especially functional foods. This has been proven with the increased extraction rate of flavonoids from Kudzu plant parts. The Kudzu plant is already known for its high flavonoid content in its food by-products; however, ultrafine pulverization boosted the bioavailability of its flavonoid bioactive components. Kudzu powder's surface area was increased through ultrafine pulverization, resulting in smaller, more rounded particles with higher solubility and flavonoid extraction rates. The rate of flavonoid extraction from Kudzu powders was significantly influenced by microwave power, ultrasonic time, and ultrasonic power, in that order. This study provides useful combinatory processing techniques as the basis for the application of ultrafine Kudzu particles as functional foods.

## Author contribution statement

He Zhu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

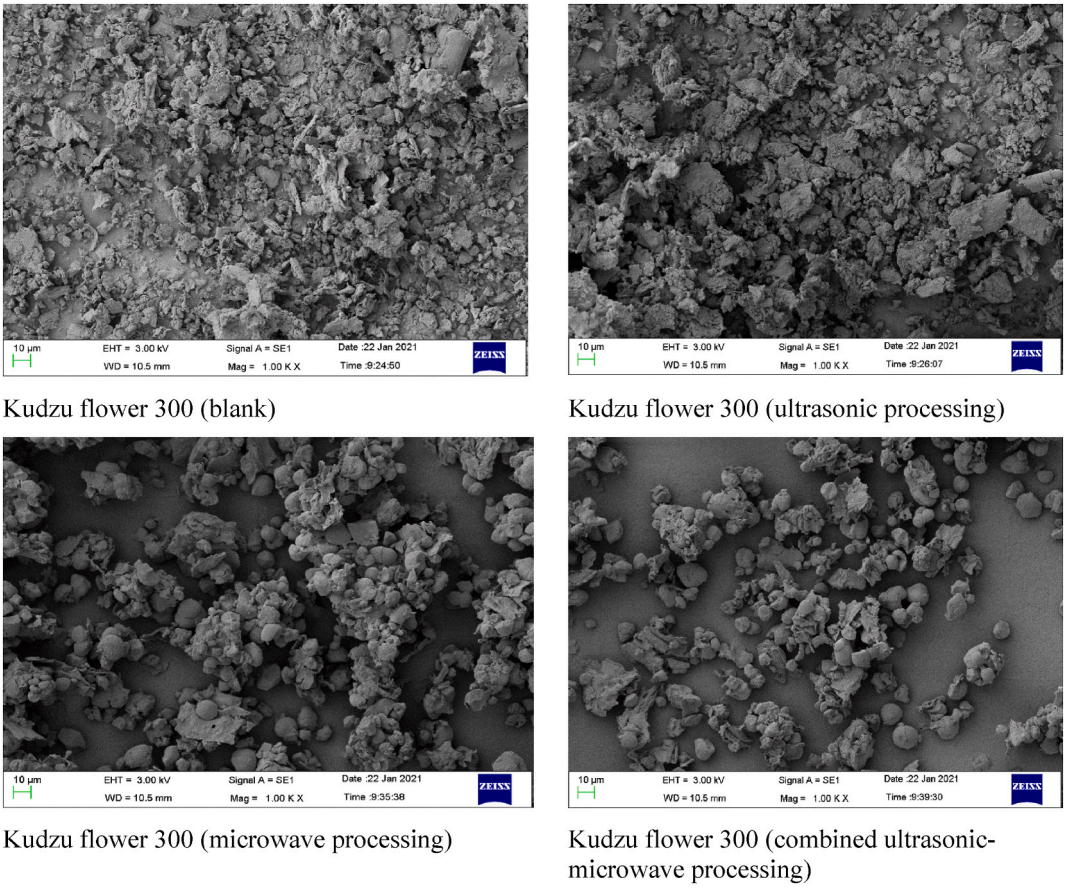



**Fig. 4.** (*continued*).

Yanxia Xing: Performed the experiments; Wrote the paper.
Otobong Donald AKAN: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Tao Yang: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

## Data availability statement

Data included in article/supplementary material/referenced in article.

## Institutional review board statement

Not applicable-because studies did not involve animal models or humans.

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## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Tao Yang reports financial support was provided by Central South University of Forestry and Technology. Prof Tao Yang reports a relationship with Central South University of Forestry and Technology that includes: non-financial support. No additional information at this time.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e21137.

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