



Investigation of the Extraction Parameters on Acquisition of Natural Colorants from *Coleus atropurpureus* L. Benth Leaves Using Microwave- and Ultrasonic-Assisted Extraction

Yuyun Yuniati¹, Selfina Gala², Sumarno Sumarno³, Mahfud Mahfud^{3#}

¹Food Technology Study Program, Faculty of Agriculture, Dr. Soetomo University, Semolowaru No. 84, Surabaya 60118, Indonesia

²Chemical Engineering Study Program, Fajar University, Jl. Prof. Abdurrahman Basalamah No. 101, Makassar 90231, Indonesia

³Department of Chemical Engineering, Institut Teknologi Sepuluh Nopember, Jl. Arief Rahman Hakim, Surabaya 60111, Indonesia

#Corresponding author: E-mail: mahfud@its.ac.id

Abstract— This study systematically investigates the application of Microwave-Assisted Extraction (MAE) and Ultrasonic-Assisted Extraction (UAE) to extract natural pigments from *Coleus atropurpureus* L. Benth leaves, using water as a green solvent. These advanced techniques were selected over conventional methods due to their well-documented advantages, including shorter extraction times, higher extraction efficiencies, and reduced environmental impact through lower solvent consumption. Importantly, MAE and UAE are particularly suitable for isolating thermolabile compounds such as plant pigments, as they minimize thermal degradation while enhancing yield. Key extraction parameters (feed-to-solvent ratio (F/S), particle size, extraction time, temperature, microwave power, and ultrasonic frequency) were systematically varied to evaluate their influence on extraction performance. Additionally, an air flow system was integrated into both setups to study the effect of controlled airflow (1 to 4 L/min) on pigment yield. For MAE, optimal conditions included 400 W microwave power, an F/S ratio of 0.01 g/mL, particle size greater than 40 mesh, 40 minutes extraction time, and an airflow rate of 1 L/min. In the case of UAE, maximum yield was achieved at a frequency of 40 kHz, extraction temperature of 60°C, F/S ratio of 0.01 g/mL, 25 minutes extraction time, and an airflow rate of 1 L/min. The resulting extracts were characterized using phytochemical screening, Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and gas chromatography (GC). Kinetic modeling, employing first- and second-order equations, demonstrated that the second-order kinetic model provided a better fit for both MAE and UAE processes, indicating complex interactions between solute and solvent. Overall, this study highlights the potential of MAE and UAE as efficient, eco-friendly alternatives for pigment extraction from *Coleus* leaves.

Keywords— *Coleus atropurpureus*, Microwave-Assisted Extraction, Ultrasonic-Assisted Extraction, Natural Colorants, Extraction

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I. INTRODUCTION

The existence of colorant raw materials has contributed significantly to various applications, from textile products, pharmaceuticals, to food and beverages [1]. Being a strategic element in product appearance has increased the growth of this

business for centuries [2]. Synthetic colorants are more commonly used than natural colorants because they are able to provide a wider variety of color categories at lower production costs. [3]. However, the challenges of using synthetic colorants related to health risks and environmental pollution highlight the return to using natural colorants today [4]. Safer, healthier, and

more sustainable natural colorants are currently progressively relevant in meeting market demand [5].

Indonesia, with its rich biodiversity, has excellent capability as a source of natural colorants [6, 7]. This country has a variety of plant species that contain variations in the composition of pigments from fruits, flowers, leaves, wood, bark, and roots that have not been fully explored [8]. One of the plants that has the potential to be studied for its colorants is the *Iler* leaf (*Coleus atropurpureus* L. Benth). In the last two decades, this plant has been studied for its chemical composition to promote its health benefits [9, 10]. Its colorful and striking leaves have the potential as a source of colorants, in addition to being ornamental plants [11]. The use of *Iler* leaves as a natural colorant can support biodiversity conservation and be a solution to reduce dependence on synthetic colorants [12].

To obtain natural colorants from plants, an effective extraction method is needed to maximize the extraction of pigments from plant tissue [13]. Conventional extraction methods, such as maceration or Soxhlet, have been commonly used to obtain extract substances even though they have disadvantages, such as extended time usage, excessive solvent volume, and low efficiency [14]. Therefore, innovations in extraction methods continue to be developed to increase yields by maximizing energy efficiency, time, and solvent use [15, 16]. Methods such as MAE and UAE were created to accelerate the extraction process by increasing the penetration of small amounts of solvents into plant tissues, thereby accelerating the release of colorants [17, 18]. With the ability to produce more optimal extraction results, the microwave and ultrasonic extraction methods are expected to produce natural colorants from *Iler* leaves that can be applied in food products.

Coleus plants (*Solenostemon scutellarioides*) display vibrant leaf pigmentation due to the presence of chlorophylls, anthocyanins, and carotenoids—each offering distinct spectral and bioactive properties. Chlorophyll *a* is the main photosynthetic pigment, absorbing blue and red light for energy conversion [19]. Anthocyanins, responsible for red to purple hues, protect against UV radiation and exhibit antioxidant activity [20]. Carotenoids like beta-carotene and lutein absorb light in the blue range and support photoprotection, with health benefits linked to reduced cancer and cardiovascular risk [21].

Previous studies on the extraction of *Iler* (*Coleus atropurpureus*) leaves remain limited, with only a few reports focusing on conventional methods such as maceration, reflux, and microwave-assisted extraction using 70% ethanol as a solvent [22] as well as solvent variation studies [23]. However, these studies did not comprehensively investigate the key parameters influencing extraction efficiency. In contrast, the present study introduces notable advancements by employing water as the primary solvent—an environmentally friendly alternative to organic solvents. Water's higher dielectric constant ($\epsilon = 80.4$) compared to ethanol enhances its suitability for extracting natural colorants from *Iler* leaves, especially for food-related applications [24]. This research

adopts a more comprehensive approach by systematically evaluating the effects of critical extraction variables, including feed-to-solvent ratio (F/S), microwave power, ultrasonic frequency, particle size, temperature, and extraction time, on the extract yield. Additionally, an innovative aspect of this study is the development of modified extraction systems: Microwave Air-Assisted Extraction (MAAE) and Ultrasonic Air-Assisted Extraction (UAAE), achieved by integrating an air flow into the extraction setup. Inspired by earlier work [25], this modification enhances extraction performance by accelerating cell wall disruption through airflow, thereby increasing extraction yield [26].

This research takes a comprehensive approach by thoroughly investigating the influence of critical extraction variables, including the solid-to-solvent ratio (F/S), microwave power, ultrasonic frequency, particle size, extraction temperature, and time, on the yield of *Iler* leaf extracts. The advantages of MAE and UAE, such as enhanced extraction efficiency, reduced solvent consumption, and preservation of bioactive compounds, have been explicitly stated. We also emphasized their suitability for water-based extraction, aligning with the study's focus on eco-friendly methods, and that these polar pigments are well-suited for water-based extraction under MAE and UAE conditions. Another key innovation is the development of modified extraction systems, Microwave Air-Assisted Extraction (MAAE) and Ultrasonic Air-Assisted Extraction (UAAE), by integrating an air flow. This novel technique, inspired by previous research [27], involves cell wall disruption through airflow, thereby accelerating the extraction process and improving extract yield [26].

Furthermore, this study goes beyond yield optimization by providing a detailed analysis of extraction kinetics, comparing first- and second-order models to better understand the mechanisms governing compound diffusion. It also explores the physical and chemical properties of *Iler* leaf extracts through advanced characterization techniques, including phytochemical analysis, infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and gas chromatography (GC). These findings offer new insights into sustainable and efficient extraction methods, with significant potential applications in the food industry.

II. MATERIALS AND METHODS

A. Materials

Iler leaves (*Coleus atropurpureus* L. Benth), aged 45–60 days, cultivated under pesticide-free condition, used in this study were obtained from Makassar, South Sulawesi. The leaves were in a semi-dry form (dried at room temperature for 24 hours), which were then subjected to a size reduction process until sieving. Analytical grade aquades was the main solvent in the process of extracting the *Iler* leaf colorant. Several chemicals, such as magnesium powder, concentrated hydrochloric acid solution (HCl), ferric chloride solution (FeCl₃), sodium chloride

(NaCl), and potassium hydroxide solution (KOH), were used for phytochemical testing of the colorant. All materials were analytical grade (Merck), as shown in **Table 1**.

TABLE 1.
 REAGENTS USED FOR PHYTOCHEMICAL TESTING

Phytochemical Group	Reagent Used	Reaction Indication / Color Change	Reference Purpose
Flavonoids	Mg + HCl	Pink/red coloration	Detection via metal-flavonoid complex
Tannins	Ferric chloride (FeCl ₃)	Dark green / blue-black complex	Phenolic group interaction
Phenolics	Folin-Ciocalteu reagent	Blue color (measured at 765 nm)	Total phenolic quantification
Alkaloids	Dragendorff's reagent	Orange-red precipitate	Precipitation of alkaloid-ion complexes
Steroids/ Triterpenoids	Liebermann-Burchard	Pink to green coloration	Cholesterol ring system interaction
Saponins	Distilled water + shaking	Persistent frothing	Surface activity due to glycoside content
Terpenoids	Chloroform + H ₂ SO ₄	Reddish-brown interface	Reaction with concentrated acid layer

B. Experimental Apparatus

Figure 1 (a) and **(b)** present the experimental setups for the extraction of leaf colorants using both microwave-assisted and ultrasonic-assisted methods. The microwave system used in this study is an Electrolux Microwave Oven (model EMM2007X), operating at a magnetron frequency of 2450 MHz (2.45 GHz) and adjustable power levels ranging from 100 to 800 watts. The unit operates at a voltage of 220 V, with dimensions of 46.1 x 28 x 37.3 cm. For ultrasonic extraction, an Ultrasonic Cleaner (KRISBOW model KW1801033) was employed, with specifications of 240 V, 50 Hz, 100 W, and dual frequency options of 20 and 40 kHz. The ultrasonic unit has a tank capacity of 2.8 L, (235 x 135 x 100 mm) and an outer unit size of 265 x 165 x 240 mm. Both microwave and ultrasonic extractions were carried out in a three-neck round-bottom flask reactor, equipped with a condenser. The temperature was continuously monitored using a K-type thermocouple (1/16 inch) integrated into both the microwave and sonicator systems.

In addition to the standard setup, an air flow was incorporated into the extraction apparatus, highlighted in yellow in **Figure 1**. The air flow (Melzer model V-777) features a 1/5 HP electric motor, operates at 220-240 V, and runs at a frequency of 50/60 Hz with a maximum pressure of 42.5 psi. The air pump

regulates airflow between 0.1 and 10 L/min, controlled by a flowmeter. The inclusion of this air flow is a key part of this study, as it enables the examination of the effects of introducing airflow into both microwave and ultrasonic extraction processes.

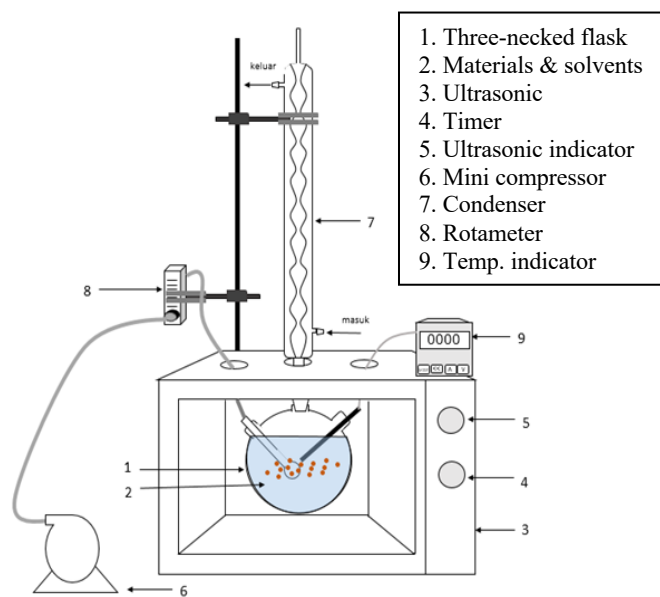


Fig. 1 (a) Schematic of Extraction Equipment using Microwave.

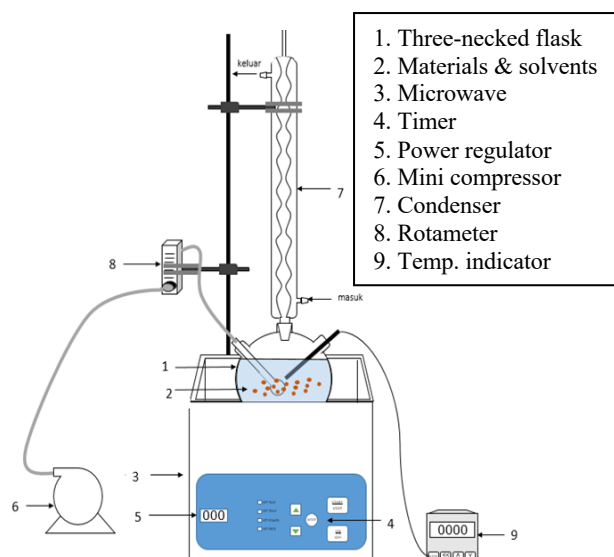


Fig. 1 (b) Schematic of Extraction Equipment using Ultrasonic.

a. Extraction Procedure

The extraction of *Iler* leaf colorants using the microwave method involved preparing the leaf powder in three particle sizes: 31-34 mesh, 36-39 mesh, and greater than 40 mesh. *Iler* leaf powder and distilled water were added to the extraction flask in varying solid-to-solvent ratios of 0.01, 0.02, 0.04, 0.06, 0.08, and 0.1 g/mL. The microwave was then operated at three different power settings: 264 W, 400 W, and 600 W. Airflow

rates were set at 0, 1, 4, 7, and 10 L/min. The extraction process was conducted at intervals of 1, 3, 5, 10, 20, 30, 40, 50, and 60 minutes. After each extraction, the colorant extract was filtered using filter paper, concentrated, and then dried in a Memmert oven at 60 °C until fully dry. The resulting dried color extract was weighed, and the yield was calculated using Equation 1

$$\% \text{ Colorant Yield} = \frac{\text{berat ekstrak zat warna}}{\text{berat bahan serbuk}} \times 100\% \quad \text{Eq (1)}$$

The extract of the color of the *Iler* leaves was stored in a vial bottle and placed in a refrigerator with a temperature range of 4 - 8 °C, before being used for further testing.

The procedure for extracting *Iler* leaves using the ultrasonic method follows a similar approach to the microwave method, with key differences in raw material preparation and equipment operation. The solid-to-solvent ratios used were 0.01, 0.02, 0.03, 0.04, and 0.05 g/mL, while the raw material particle size remained consistent at greater than 35 mesh. The ultrasonic system was operated at frequencies of 20 kHz and 40 kHz, with extraction temperatures set at 40, 50, and 60 °C. The airflow rates used were 0 and 1 L/min. The ultrasonic extraction process was conducted for the same time intervals, and the procedures for handling, filtering, concentrating, drying the colorant extracts, and calculating yield were identical to those described in the microwave extraction procedure.

b. Physical and Chemical Characteristics of Color Extract

The color extract samples of the *Iler* leaves were tested using FTIR, GCMS, and SEM. FTIR testing was carried out by dropping the extract sample on a plate and analyzed with FTIR (Thermo Scientific, Nicolet IS10, spectral range 4500–400 cm⁻¹) to determine the functional groups in the *Iler* leaves before and after extraction. The colorant extract was analyzed for volatile compound content using GCMS (Hewlett–Packard 6890 connected to a 5973A mass spectrometer) using a silica capillary column. Analysis of the surface morphology of the raw material powder and solid residue after the extraction process using SEM (FEI, Type Inspect-S50) by placing the sample with a thin layer of gold (Au).

c. Phytochemical Test of *Iler* Leaf Extract

Phytochemical tests were carried out qualitatively to detect the presence of flavonoids, tannins, and quinones in the extract of *Iler* leaves. Qualitative flavonoid tests use the Shinoda principle, in which the extract of *Iler* leaves is reacted with magnesium powder and concentrated hydrochloric acid to observe the color change to red, which indicates the presence of flavonoids [28]. Qualitative tannin tests were carried out by adding a few drops of ferric chloride solution and salt to the extract of *Iler* leaves to see the color change to dark blue or blackish green as an indication of the presence of tannins [29]. Qualitative quinone tests were carried out by mixing a strong base solution of potassium hydroxide into the extract of *Iler* leaves, which

produced a red color as an indication of the presence of quinones [30].

d. Phytochemical Test of *Iler* Leaf Extract

Phytochemical tests were carried out qualitatively to detect the presence of flavonoids, tannins, and quinones in the extract of *Iler* leaves. Qualitative flavonoid tests use the Shinoda principle, in which the extract of *Iler* leaves is reacted with magnesium powder and concentrated hydrochloric acid to observe the color change to red, which indicates the presence of flavonoids [28]. Qualitative tannin tests were carried out by adding a few drops of ferric chloride solution and salt to the extract of *Iler* leaves to see the color change to dark blue or blackish green as an indication of the presence of tannins [29]. Qualitative quinone tests were carried out by mixing a strong base solution of potassium hydroxide into the extract of *Iler* leaves, which produced a red color as an indication of the presence of quinones [30].

e. Kinetics Analysis of *Iler* Leaf Extract

The kinetics of colorant extraction for all extraction methods were studied for first and second order reactions [31]. The first order kinetic equation, according to Lagergen was studied through the integrated rate equation:

$$\log(C_s - C_t) = \log(C_s) - \frac{k_1}{2,303} t \quad \text{Eq (2)}$$

With t is the extraction time, k_1 (min⁻¹) is the first-order reaction kinetic constant, C_s is the extraction capacity value, and C_t is the extraction value at time t . Then, a straight line plot is made with $\log(C_s - C_t)$ and t data, so as to obtain slope and intercept values that can be used in determining the values of k_1 and C_s .

The second-order kinetic model is carried out by making a straight-line plot between t/C_t and t based on the integrated rate equation:

$$\frac{t}{C_t} = \frac{t}{C_s} + \frac{1}{k_2 C_s^2} \quad \text{Eq (3)}$$

The value of k_2 (L.g⁻¹.min⁻¹) and C_s can be calculated from the slope and intercept values of the straight-line plot obtained. The straight-line equation that has the highest coefficient of determination is the reaction order selected in analyzing the kinetic model of the extraction process.

III. RESULT AND DISCUSSION

C. Effect of variables on the yield extract (microwave)

Microwave-Assisted Extraction (MAE) offers significant advantages by accelerating extraction time and increasing yield with lower energy consumption compared to conventional extraction methods [32]. In this study, *Iler* leaf extraction using the microwave method was optimized by investigating several key parameters, including the solid-to-solvent (F/S) ratio, microwave power, particle size, extraction time, and airflow

rate. The extract yields obtained under different conditions were compared to determine the optimal settings for maximizing yield.

The first parameters examined were the F/S ratio and microwave power. **Figure 2** shows the effect of varying the feed-to-solvent ratios on extract yield across different microwave power levels.

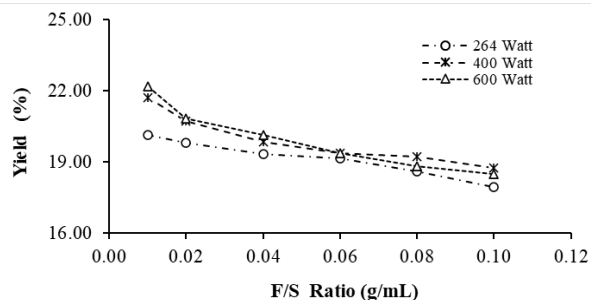


Fig. 2 Effect of the feed to solvent ratio on the yield (t=10 min, >40 mesh)

As the F/S ratio increased, a general decrease in the yield of *Iler* leaf extract was observed. The optimal yield was achieved at a ratio of 0.01 g/mL (mass/volume) and a microwave power of 600 W, resulting in a yield of 22.17%.

In general, a smaller material-to-solvent (F/S) ratio in the extraction system allows more solvent to come into contact with the material, facilitating greater extraction of colorants. A larger solvent volume causes the material to swell, making it easier for cell walls to break down and release colorants into the solvent, which results in a higher extraction yield [33]. Additionally, water's high dielectric constant enhances the efficiency of microwave-assisted extraction [24].

As shown in **Figure 2**, using 600 W of microwave power produced the highest yield, particularly when the F/S ratio was low, compared to 264 W and 400 W. Microwave power controls the amount of heat energy delivered to the solvent, which aids in breaking down cell walls and releasing intracellular compounds from the *Iler* leaves. At higher microwave power, the water molecules experience greater radiation, leading to increased molecular collisions and rotations, which in turn improve the extraction yield [32]. However, at higher F/S ratios (0.08 and 0.1 g/mL), 600 W power resulted in a significant decrease in yield compared to 400 W. This decrease is likely due to the thermolabile nature of certain components in *Iler* leaves, which degrade at higher temperatures [34]. Therefore, microwave power above 400 W is not recommended for extracting natural colorants from *Iler* leaves, as 400 W provides a more consistent and efficient yield profile overall.

Figure 3 demonstrates the effect of particle size, as determined by sieving *Iler* leaf powder through 31-34 mesh, 36-39 mesh, and >40 mesh sieves, on extract yield after 10 minutes of extraction at 264 W microwave power. The data shows that smaller particle sizes resulted in higher yields. The optimum

particle size for colorant extraction was achieved using >40 mesh sieve, yielding 20.31% under F/S conditions of 0.01 g/mL. Finer particle sizes increase the surface area of the material in contact with the solvent, enhancing extraction efficiency [26].

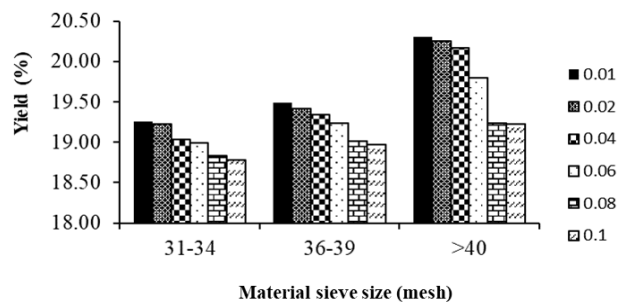


Fig. 3 Effect of the size on the yield of colorant (t=10 min, 264 W)

Figure 4 shows the effect of extraction time on the yield of the colorant extract. The highest yield was obtained after 40 minutes of extraction, with a yield of 23.56%. This time point is considered the optimal duration for the diffusion of the solvent into the *Iler* leaf tissue matrix. Beyond 40 minutes, a decline in yield was observed, indicating that prolonged extraction using Microwave-Assisted Extraction becomes less effective. This reduction may be due to the degradation of bioactive components caused by prolonged exposure to heat generated by the microwave, which diminishes the colorant yield [26].

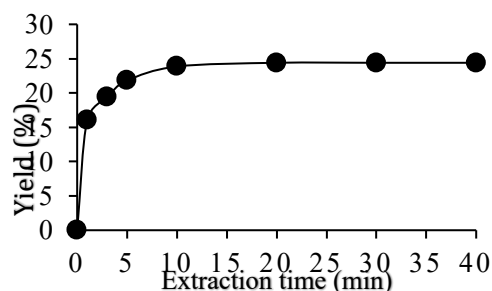


Fig. 4 Effect of extraction time on extract yield (400 W, F/S 0.01 g/mL, size: >40 mesh)

Another parameter explored in the microwave-based extraction process was the addition of airflow, referred to as Microwave-Assisted Air Injection Extraction. This experiment introduced airflow at rates of 4, 7, and 10 L/min, while keeping other conditions constant: microwave power of 600 W, a material-to-solvent ratio of 0.06 g/mL, an extraction time of 30 minutes, and particle size greater than 35 mesh. **Figure 5** shows the effect of different airflow rates on the extraction yield. The optimum yield of 19.84% was achieved at an airflow rate of 4 L/min. However, higher airflow rates of 7 and 10 L/min resulted in decreased yields, likely due to excessive turbulence in the extraction system, which inhibited effective contact between the solvent and the material [26].

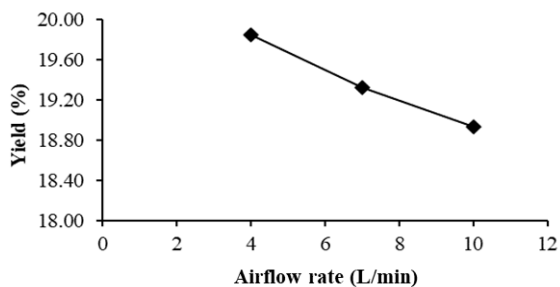


Fig. 5 Effect of airflow rate on the yield of Iler leaf extract (600 W, F/S 0.06 g/mL, 30 min).

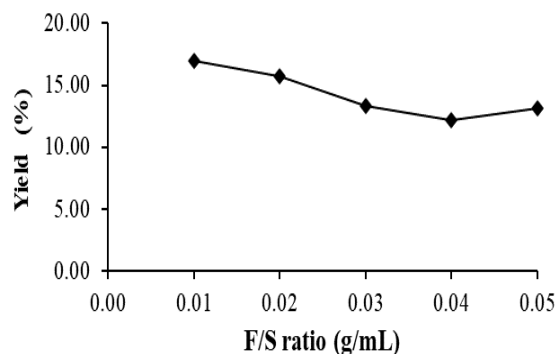


Fig. 6 Effect of the ratio of Iler leaf material on the extraction yield (40 kHz, 10 min, F/S: 0.01 g/mL, material size <35 mesh)

D. Effect of variables on the yield extract (ultrasonic)

Ultrasonic-Assisted Extraction (UAE) is also recognized as an effective method for enhancing the mass transfer of active compounds into solvents, alongside Microwave-Assisted Extraction. By employing ultrasonic waves, UAE induces acoustic cavitation, which disrupts plant cell walls and facilitates the release of bioactive compounds [35]. In this study, key parameters such as ultrasonic frequency, the solid-to-solvent (F/S) ratio, extraction temperature, and time were investigated to optimize the yield of the extract.

The first parameter examined was ultrasonic frequency, comparing the effects of 20 kHz and 40 kHz frequencies on extraction yield, while other variables were kept constant (F/S ratio of 0.01 g/mL, extraction time of 10 minutes, and raw material size >40 mesh). The extraction yield at 20 kHz was 15.82%, whereas the yield at 40 kHz reached 17.00%. The higher frequency of 40 kHz generated larger microbubbles with greater energy and pressure, leading to more effective disruption of the plant cell walls [36]. In contrast, 20 kHz was found to be less efficient for extracting colorants from Iler leaves.

Figure 6 shows the effect of the F/S ratio on extraction yield. The ratio of 0.01 g/mL was determined to be the optimal F/S ratio for extracting natural colorants from *Iler* leaves. The results from the ultrasonic extraction mirrored the trends observed in the Microwave-Assisted Extraction process. As the F/S ratio increased, the solvent's viscosity also increased, which inhibited the formation of microbubbles and reduced the breakdown of plant cell walls. This diminished the solvent's ability to penetrate the plant material and extract bioactive compounds efficiently [37].

Figure 7 highlights the impact of temperature and extraction time on the yield of the colorant extract. Extraction at 60°C produced a better yield profile compared to the other tested temperatures, with the maximum yield of 17.61% achieved after 25 minutes. Increasing the extraction temperature reduces the surface tension of the material, lowering the cavitation threshold, which facilitates bubble formation. The rupture of these bubbles further disrupts plant cell walls, enhancing solvent diffusion into the material, thus increasing the yield [38].

Similarly, extending the extraction time increases contact between the solvent and raw materials, promoting better extraction [17]. However, **Figure 7** also shows that after 25 minutes, the yield plateaus or decreases slightly, suggesting that most colorant components have already been released. Prolonged extraction may lead to the degradation of bioactive components due to excessive ultrasonic exposure [38]. The effect of extraction time is explored in more detail in the subsequent discussion on extraction kinetics.

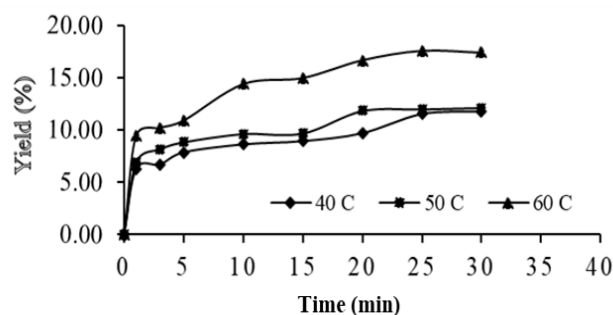


Fig. 7 Effect of Iler leaf extraction temperature on extraction yield using aquades solvent in UAE (Frequency 40 kHz, F/S: 0.01 g/mL, material size: >40 mesh)

The influence of airflow was also investigated in ultrasonic-based extraction, referred to as Ultrasonic Air-Assisted Extraction (UAAE). **Figure 8** presents the extraction yield profile of *Iler* leaves after 30 minutes, both with and without airflow. During the first 20 minutes, the yield profiles of both systems were comparable, with no significant differences. However, after 20 minutes, airflow at a rate of 1 L/min began to show a more optimal yield profile compared to the system without airflow. It is hypothesized that this moderate airflow supports better solvent diffusion into the *Iler* leaf tissue, improving the overall extraction efficiency.

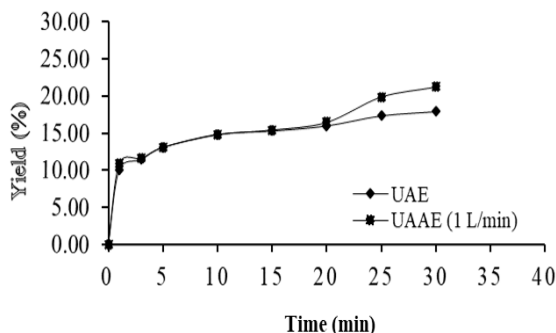


Fig. 8 The effect of airflow on the yield of *Iler* leaf extract (40 kHz, F/S 0.01 g/mL, material size: >40 mesh)

E. Physical and Chemical Characteristics Test of *Iler* Leaf Extract

Qualitative analysis of functional groups in *Iler* leaves before and after extraction by microwave method was done by observing the absorption peak of infrared spectrum. FTIR spectra of *Iler* leaf material at 400-Watt power, 10 minutes time, (a) before extraction, (b) after extraction with MAE, have been conveyed in previous papers [23]. The FTIR spectra of *Iler* leaf material before and after Microwave-Assisted Extraction (MAE) at 400-Watt power for 10 minutes reveal significant chemical changes. Before extraction, prominent peaks corresponding to O-H (3419 cm^{-1}), C-H (2923 cm^{-1}), C=O (1653 cm^{-1}), and C-O (1234 cm^{-1}) indicate the presence of phenolics, flavonoids, and terpenoids. After extraction, reduced intensities in hydroxyl and carbonyl peaks suggest the removal of bioactive compounds. Shifts in ester and ether regions confirm structural alterations, while new peaks in the fingerprint region indicate modifications in aromatic components. These findings demonstrate MAE's efficiency in extracting phytochemicals while preserving key functional groups.

To evaluate the chemical composition and structural changes of bioactive compounds extracted using UAE, we performed FTIR analysis on the *Iler* leaf extract obtained under optimal UAE conditions (frequency 40 kHz, extraction time 25 minutes, temperature 60°C , F/S ratio 0.01 g/mL, particle size >40 mesh). The spectrum exhibited characteristic absorption peaks at $\sim 3417\text{ cm}^{-1}$ (O-H stretch), 2920 cm^{-1} (C-H stretch), 1650 cm^{-1} (C=O stretch), and 1232 cm^{-1} (C-O stretch). These peaks are consistent with the presence of flavonoids, terpenoids, and phenolic compounds and align with those identified in the MAE extract. However, the peak intensities in the UAE spectrum were slightly lower, indicating less extensive cell wall disruption and potentially reduced release of intracellular compounds compared to MAE. This observation is consistent with the lower extraction yield values reported in **Table 2**.

Ultrasound-Assisted Extraction (UAE) is a well-established technique for extracting bioactive compounds from plant

materials, offering optimized yield while reducing extraction time and solvent consumption. The FTIR spectral analysis of *Iler* leaf extract under optimal UAE conditions supports this, showing key functional group signatures similar to those found in MAE extracts. These findings are consistent with previous reports on phytochemical profiles obtained via both MAE and UAE [39][22].

In addition to studying the physical characteristics of the product with infrared spectrum absorption, which showed the presence of specific functional groups, observations of the morphology of the surface of the *Iler* leaves were carried out before and after being extracted with microwaves using Scanning Electron Microscopy at a magnification of 1.00 kx. **Figure 9a** shows the appearance of coarse powder of the *Iler* leaf material before extraction, which reveals a horizontal surface structure in the form of thin slices with narrow gaps. In contrast, the image of the *Iler* leaf extract shown in **Figure 9b** indicates that the microwave extraction process has significantly altered the surface structure of the *Iler* leaves, resulting in a thinner surface with deeper and wider concave gaps, as well as a broken and cracked appearance.

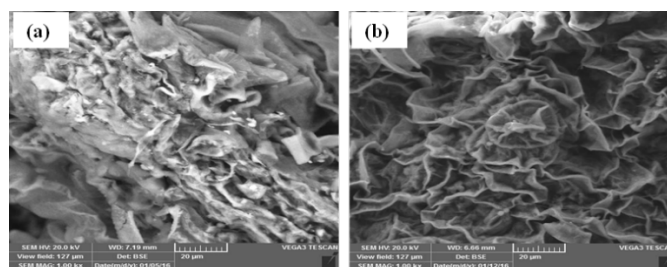


Fig. 9 Morphology of 20 µm *Iler* leaf powder with SEM magnification of 1000x in: (a) powder before extraction, (b) powder after extraction with MAE (P=264 W, t= 10 minutes)

In general, damage to the surface structure of the color extract substance after being extracted with a microwave can be caused by polar molecules in the material being exposed to microwave radiation energy. During the extraction process, there is an oscillatory movement and collision between the solvent and the *Iler* leaves. This causes the cell wall to be damaged and forms a cavity from the surface of the material into the tissue. Damage to the material structure enhances extract diffusion, liquid penetration, component release, and mass transfer [40]. The results of the identification of volatile compounds based on gas chromatography testing for *Iler* leaf extract, which can be detected to contain 1H-Cycloprop[e]azulen-4-ol, decahydro-1, 1,4,7-tetramethyl-, [1ar-(1a.alpha.,4.beta.,4a.b), 2-Hexadecene-1-ol, 3,7,11,15-tetramethyl-, [R-[R*,R*-(E)]], Stigmast-5-En-3-Ol, (3.Beta.,24s)-, Benzenepropanoic acid, 3,5-bis(1,1-dimethylethyl)-4-hydroxy-, methyl ester, 2-Norpinanol, 3,6,6-trimethyl-, Ethyl iso-allocholate, Stigmast-5-en-3-ol, (3.Beta.,24S)-, Phytol.

II. PHYTOCHEMICAL TEST OF ILER LEAF EXTRACT

Qualitative analysis of the presence of flavonoid, tannin and quinone pigments was conducted because these three pigments were indicated to be contained in the extract of *Iler* leaves. The results of the test of colorants in the extract of *Iler* leaves extracted by microwave are shown in **Table 1**. The extract of *Iler* leaves contains flavonoids and tannins but is suspected of not containing quinones. In the qualitative test of flavonoids, after the extract of *Iler* leaves was added with Mg and HCl powder, it produced a yellow color. The addition of NaCl and FeCl₃ to the extract of *Iler* leaves during the tannin test resulted in a blackish green color. However, when NaOH was added to the *Iler* leaf extract, the resulting color was not red, but yellowish green. Phytochemical screening of the UAE extract was also carried out using the same qualitative test protocol as that applied to the MAE extract. The results are summarized below and included in **Table 2**. This confirms that UAE, like MAE, is capable of extracting flavonoids and tannins, with no indication of quinone presence. This qualitative consistency further strengthens the comparison between the two methods.

Previous literature supports the notion that extraction conditions, such as frequency, time, temperature, and material characteristics, play a critical role in determining the efficiency of bioactive compound recovery [22], [41]. The observation of lower peak intensities during UAE compared to MAE may indicate less severe cell wall disruption, leading to reduced intracellular compound release. This aligns with findings from previous studies that highlight the relationship between extraction methodologies and phytochemical yield, where methods like MAE demonstrate higher extraction efficiencies due to more effective cell lysis [22], [41], [42].

TABLE 2

RESULTS OF PHYTOCHEMICAL TEST OF EXTRACT WITH MAE & UAE

Pigment	Reagent	Observation	Test Results
MAE			
Flavonoid	Mg + HCl Powder	Yellow	++ (available)
Tannin	NaCl + FeCl ₃	Blackish green	+ (available)
Quinone	NaOH	Yellowish green	- (not available)
UAE			
Flavonoid	Mg + HCl Powder	Yellow	++ (available)
Tannin	NaCl + FeCl ₃	Blackish green	+ (available)
Quinone	NaOH	Yellowish green	- (not available)

Moreover, studies emphasize that the structural integrity of cell walls can affect the release of bioactive compounds. Consequently, techniques such as UAE may not achieve the same level of extraction efficiency as more aggressive methods

like MAE, particularly for compounds that are sensitive to prolonged heat exposure or intensive mechanical forces [43] [44] [42]. This is further corroborated by extraction yield data reported in prior research, where MAE exhibited superior performance over UAE under similar conditions, particularly with regard to flavonoid content and antioxidant potential [22] [42] [45].

Therefore, the analysis of the *Iler* leaf extract through FTIR under optimal UAE conditions reveals promising results consistent with reported phytochemicals while indicating the need to balance extraction intensity and yield in optimizing bioactive compound recovery. Further comparative studies between extraction methods may provide deeper insights into maximizing phytochemical extraction without compromising the structural composition of sensitive compounds.

III. KINETICS OF ILER LEAF COLORANT EXTRACTION BASED ON MICROWAVE AND ULTRASONIC

The study of extraction kinetics models, such as first-order and second-order models, serves as a mean to evaluate the effectiveness of extraction methods based on extraction time. The extraction yields of *Iler* leaf extract were compared for Microwave Assisted Extraction (MAE), Microwave Air Assisted Extraction (MAAE), Ultrasonic Assisted Extraction (UAE), and Ultrasonic Air Assisted Extraction (UAAE) methods. All extractions were conducted for 30 minutes, maintaining a F/S value of 0.01 g/mL, material size >40 mesh, power of 400 Watts (MAE and MAAE) and 40 kHz (UAE and UAAE), and airflow rates of 1 L/min (MAAE and UAAE). **Table 3** summarizes the results of the yield measurements.

TABLE 3

COMPARISON OF THE YIELD USING MAE, MAAE, UAE, AND UAAE METHODS

Extraction Time (minutes)	Extract Yield (%)			
	MAE	MAAE (1 L/min)	UAE	UAAE (1 L/min)
1	12.03	16.01	10.05	9.49
3	15.54	19.40	11.45	10.22
5	19.09	21.80	13.09	10.92
10	21.70	23.85	14.87	14.84
20	22.33	24.40	16.01	16.72
30	23.10	23.08	17.94	17.44

Table 3 shows that the yield of *Iler* leaf extract obtained using microwave-based methods is greater than that obtained using ultrasonic-based methods. This difference is likely attributed to the superheating effect generated within the extraction flask during microwave application, combined with the use of water as a solvent, which has a high dielectric constant, and the relatively high-power output of the microwave oven. Superheating can cause rapid internal and external damage to the *Iler* leaf surface [46]. Ultrasonic extraction, on the other hand, is primarily influenced by ultrasonic wave energy [40].

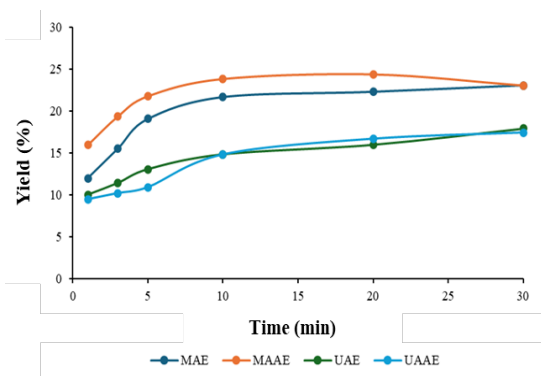


Fig. 10 Comparison profile of the yield of *Iler* leaf extract using the MAE, MAAE, UAE, and UAAE methods for 30 minutes of extraction time.

The extraction kinetics model was analyzed based on time and yield data. **Figure 10** compares the yield profiles of *Iler* leaf extract using MAE, MAAE, UAE, and UAAE over 30 minutes. The first-order model was evaluated by plotting $\log(C_s - C_t)$ vs. t , followed by linearization to determine k_1 (min^{-1}) and C_s (g/L). Similarly, the second-order model was assessed by plotting t/C_t vs. t , with linearization yielding k_2 ($\text{L}\cdot\text{g}^{-1}\cdot\text{min}^{-1}$) and C_s (g/L). The best-fit kinetic model was determined based on the coefficient of determination (R^2) for each model as shown in **Table 4**.

TABLE 4
 RESULTS OF THE FIRST AND SECOND ORDER EXTRACTION KINETICS
 CONSTANTS OBTAINED BY THE MAE, MAAE, UAE, AND UAAE
 METHODS.

Method	Slope	k	Intercept	C_s	R^2
1 st order model					
MAE	0.0417	0.0960	1,1099	12.9795	0.9121
MAAE	0.0227	0.0523	0.7365	5,4513	0.3827
UAE	0.0144	0.0332	1,1996	12.9795	0.7936
UAAE	0.0226	0.0520	1,2362	5,4513	0.8922
2 nd order model					
MAE	0.0410	0.0357	0.0471	24,3902	0.9980
MAAE	0.0428	0.2655	0.0069	23.4645	0.9989
UAE	0.0540	0.0390	0.0671	14,9031	0.9920
UAAE	0.0480	0.0202	0.1143	8,7489	0.9622

The MAE method was set with 400 W microwave power, the feed to solvent ratio was 0.01 g/mL, and the air rate in the MAAE method was 1 L/min. The UAE method was set with the condition of 40 kHz frequency, the feed to solvent ratio was 0.01 g/mL, and the air rate in the UAAE method was 0.8 L/min. Based on the data in **Table 4**, the 2nd-order kinetic model was found to be a more suitable model for representing the experimental results on the extraction of natural colorants from *Iler* leaves. A kinetic model is a good fit if it has a coefficient of determination value close to one. The first-order kinetic model of *Iler* leaf extraction had a relatively low R^2 value, indicating that it was less suitable for representing the experimental data [47].

IV. CONCLUSION

Natural colorant extracts from *Iler* leaves (*Coleus atropurpureus*) were successfully obtained using Microwave-Air Assisted Extraction (MAAE) and Ultrasonic-Air Assisted Extraction (UAAE). Optimization of key parameters—including F/S ratio, particle size, airflow, extraction time, and energy input—significantly influenced extraction yield. In MAAE, the combination of 0.01 g/mL F/S ratio, >40 mesh particle size, 1 L/min airflow, 400 W microwave power, and 40 minutes of extraction time provided optimal conditions. For UAAE, optimal yield was achieved using a 40 kHz frequency, a 60°C temperature, the same F/S ratio and airflow, and a 25-minute extraction time. These conditions promote efficient cell wall disruption and enhanced mass transfer.

Phytochemical screening confirmed the presence of tannins and flavonoids. FTIR analysis indicated strong hydrogen bonding interactions, while SEM revealed morphological damage, supporting effective cell rupture. Gas chromatography confirmed the release of volatile compounds. Kinetic modeling showed that both methods followed a second-order kinetic model, suggesting diffusion-controlled extraction.

These findings highlight the potential of MAAE and UAAE as efficient, scalable, and eco-friendly techniques for producing natural pigments from *Iler* leaves. The resulting extracts show potential for commercial applications in the food, cosmetic, and textile industries, where the demand for safe, plant-based colorants is steadily increasing. To realize commercial potential, future research should focus on formulation stability, incorporation into real product matrices, and shelf-life studies. Consumer acceptance testing and market feasibility assessments across diverse regions would further support commercialization. Moreover, exploring hybrid extraction methods (e.g., microwave-ultrasonic combinations) and solvent system innovations could enhance efficiency while preserving pigment integrity. Scaling up the process and evaluating its techno-economic viability are also critical next steps for facilitating industrial adoption and ensuring long-term sustainability.

CONFLICT OF INTEREST

The authors declare no conflict of interest to disclose.

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