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Sustainable Extraction of Cinnamon Phenolics through Synergy of Green Solvents and Microwave-Assisted Technology

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ABSTRACT

Increasing global awareness of environmental issues has encouraged the development of sustainable and eco-friendly methods for extracting phenolic compounds from Cinnamomum burmannii. *This study integrates Microwave-Assisted Extraction (MAE) with Natural Deep Eutectic Solvents (NaDES) as a green extraction approach. The objectives were to evaluate thermal efficiency, energy consumption, carbon emissions, and extraction kinetics at microwave powers of 640, 720, and 800 W using citric acid–sucrose as the solvent. The highest thermal efficiency (69.82%) was achieved at 640 W, with an energy consumption of 540.86 kJ and carbon emissions of 0.131 kg CO_2e. Extraction kinetics were described using the Peleg model, which accurately represented changes in phenolic concentration during extraction. The highest extraction rate constant (B_0 = 0.2117 mg/mL·min) was obtained at 640 W, while the highest equilibrium capacity constant (Ce = 0.6982 mg/mL) and total phenolic content (6.42 ± 0.046 mg GAE/mL) were achieved at 800 W. These findings indicate that increasing microwave power enhances both extraction rate and phenolic yield. Compared with conventional methods, MAE combined with NaDES demonstrated lower energy consumption and reduced carbon emissions, highlighting its potential as a sustainable extraction technology.*

1. INTRODUCTION

A tropical spice typical of Southeast Asia, which is known to have a strong and distinctive aroma and has the potential as a raw material for the extraction of bioactive compounds, is cinnamon (*Cinnamomum burmanni*) (Liu *et al*., 2021a). The bioactive compounds in the form of phenolic compounds in cinnamon have various biological activities, including as antioxidant (Rahayu *et al*., 2022), anticancer (Liu *et al*., 2021b), anti-inflammatory (Zhang *et al*., 2024), antiparasitic, antimicrobial (Deshi *et al*., 2024), and antidiabetic (Djarot *et al*., 2023). The extraction process using selected solvents can play a role in separating and isolating the phenolic compounds found in cinnamon (Ahmad *et al*., 2020). The extraction process using selected solvents plays a role in separating and isolating the phenolic compounds in cinnamon (Wang *et al*., 2024). The effectiveness of these compounds is largely determined by the extraction method used. Conventional extraction methods are still frequently used, but this method has limitations such as high energy consumption and long processing times (Ameer *et al*., 2017). Microwave-assisted extraction (MAE) was developed to overcome these issues by reducing both time and solvent consumption. The MAE method utilizes microwaves to rapidly and evenly heat cinnamon powder, thereby enhancing solvent penetration into the plant matrix and facilitating efficient diffusion of active compounds (Adeel *et al*., 2020).

The application of environmentally friendly solvents, such as Natural Deep Eutectic Solvents (NaDES), can significantly improve the efficiency and sustainability of MAE method (Bonacci *et al*., 2020). NaDES is a subclass of Deep Eutectic Solvents (DES), first introduced by Abbott *et al.* (2003), and formulated from naturally derived components such as organic acids, sugars, and polyalcohols. Compared to conventional organic solvents, NaDES offers

several advantages: it is non-flammable, non-toxic, and generally safer to handle. Additionally, NaDES serves as a more environmentally sustainable alternative to volatile solvents such as methanol (Belwal *et al*., 2020), ethanol (Segatto *et al*., 2022), and 2-methyloxolane (Cravotto *et al*., 2024). Ongoing research has led to the development of various NaDES formulations, including citric acid–sucrose NaDES (NaDES-CAS). This solvent has been reported to effectively preserve key bioactive compounds in cinnamon, including phenolics, flavonoids, saponins, and tannins (Li, 2022). The adoption of NaDES-CAS not only reduces potential environmental impacts but also aligns with the principles of *green chemistry* through the utilization of renewable raw materials and the improvement of extraction efficiency.

Previous research by Izza *et al*. (2023) on extraction using MAE and NaDES, focusing on phenolic content and kinetic aspects, did not include an analysis of energy consumption during the process. The present study extends that work by incorporating thermal efficiency analysis through mass and energy balance calculations, thereby providing a more comprehensive assessment of process performance in terms of efficiency and sustainability.

The success of solvents in accelerating the extraction is related to mass and energy transfer and their synergy with microwaves and dielectric constants, which affect extraction kinetics. Determining the optimal power is essential to achieve high extraction efficiency while minimizing energy consumption and environmental impact in sustainable green chemistry processes (Mattonai *et al.,* 2022). Heat transfer in this process is related to the extraction rate, which is indicated by the increase in TPC levels in the liquid extract, so the main objective of this study is to analyze the MAE-NaDES synergy consisting of energy efficiency, waste minimization, and increased extract bioactivity. Accordingly, the success of the extraction process through variations in MAE power and the use of NaDES CAS is expected to produce innovative and relevant environmentally friendly extraction technology for future development.

2. MATERIALS AND METHODS

2.1. Materials

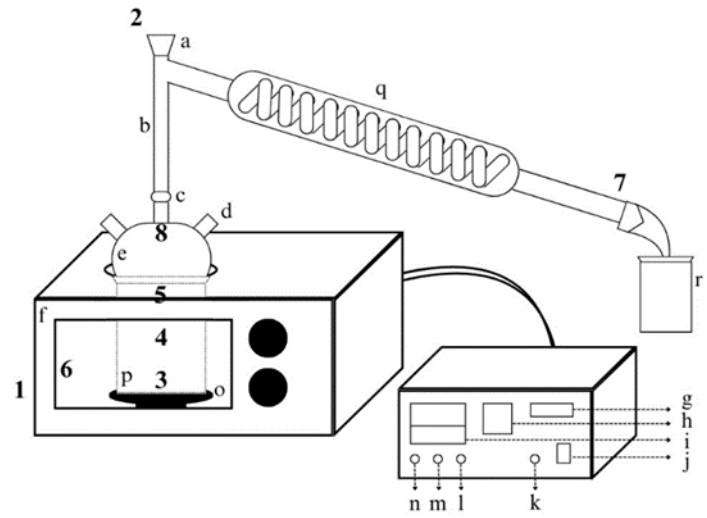
The Cinnamon bark of good quality was obtained from Beringharjo Market, Yogyakarta, Indonesia. The bark, with a moisture content of 11 ± 0.2%, was cleaned, ground, and sieved to obtain powder passing through an 80-mesh screen. The NaDES solvent was prepared by mixing 21.03 g of sucrose (purity ≥ 85%) and 34.2 g of citric acid in 100 mL of distilled water. All reagents used in this study were of analytical grade to ensure the accuracy and reliability of the extraction results. Other chemicals employed in the experiments also met analytical standards, supporting the validity of the methodology and overall research findings.

2.2. Determination of Total Phenolic Content in Extracts

The Folin–Ciocalteu procedure was applied to assess the total phenolic content (Kalpoutzakis *et al*., 2023). First, prepare the folin C 2N reagent (10%) (Maser *et al*., 2023) and 7.5% Na_2CO_3 (Sodium carbonate) solution. Second, a mixture was prepared by adding 0.5 mL of cinnamon extract to 0.2 N Folin and 7.5% Na_2CO_3 solution. Incubation was carried out for 5 minutes at a temperature of 50 °C. After incubation, cooling was carried out. Finally, with absorbance measurement using Uv Vis spectrophotometer by transferring each 1 mL reaction to the cuvette and measuring its absorbance at 765 nm after focusing on the spectrophotometer with a blank (Parntong *et al*., 2024). The TPC data results are calculated using the standard curve measurements (mg GAE/mL) (Surleva *et al*., 2024).

2.3. Extraction using MAE

The MAE system was developed by modifying an Electrolux microwave oven (EMM2308X, 23 L capacity) with a maximum output power of 800 W and an operating voltage of 220–240 V/50 Hz. The system was equipped with a control panel that enabled adjustment of temperature, microwave power, extraction time, and stirrer speed within the extraction flask (Figure 1). Temperature distribution during the MAE process was analyzed using thermocouples placed at eight strategic locations where temperature variations were expected. Temperature is a critical parameter in evaluating heat distribution; therefore, multipoint monitoring is essential for accurately assessing thermal patterns (Li *et al*., 2021). This analysis also enabled the identification of heat losses to the surrounding environment, providing insights into the system's thermal efficiency. In this configuration, the MAE heat source was considered efficient, as microwave energy was directly focused on the center of the extraction solution.



a. Condenser connecting tube
b. Condenser connecting tube and reaction flask
c. Cover hole
d. Temperature tube
e. Connecting tube
f. Microwave cavity
g. RPM screen
h. Time controller
i. P & T arranger
j. On/Off Button
k. RPM arranger
l. Timer Button
m. Indicator lamp
m. Control unit
o. Magnetic Strirrer
p. Extraction flask
q. Condenser

Figure 1. Microwave-assisted extraction for phenolics from cinnamon bark

2.4. Mass Balance Analysis

Mass balance is done by calculating the amount of material entering and the amount of material leaving an industrial production process during a certain period. The mass balance is calculated based on the mass conservation principle (Mao *et al*., 2021). This mass balance analysis starts from the weighing system, grinding, NaDES CAS homogenization, and extraction using MAE.

$$\text{Mass in} = \text{Mass out} \tag{1}$$

2.5. Energy Balance Analysis

Energy balance is an equation that describes the balance between energy input and output in a system at a given time. This concept is by the first law of thermodynamics. This law is also known as the principle of conservation of energy.

$$\text{Energy in} = \text{Energy out} \tag{2}$$

The applied microwave power affects the amount of energy released during the MAE process (Pavlić *et al*., 2023). The power generated was calculated using Equation (3).

$$Q\ (\text{joule}) = P \times t \tag{3}$$

where Q is the heat energy (J), P is the microwave power (W), and t is the heating time (s). Sensible heat refers to the heat involved in a thermodynamic process that results in a change in temperature. During the MAE heating process, the temperature increased toward the target value of 90 °C.

Sensible heat (Q_s) and latent heat (Q_l) were calculated using Equation (4) and (5), respectively. Latent heat was considered in the phase change process. It is defined as the amount of heat required to change the physical state of one kilogram of a substance without changing its temperature.

$$Q_s\ (\text{kJ}) = m \times C_p \times \Delta T \tag{4}$$

$$Q_l = m_v \times \lambda \tag{5}$$

where m is the total mass of the material (kg), C_p is the heat capacity (kJ/kg °C), and ΔT is the temperature difference (°C), m_v is the mass evaporation (kg), and λ is the latent heat of water (kJ/kg).

2.6. Evaluating the Impact of Energy Consumption on the Environment

Global Warming Potential (GWP) was used as a quantitative indicator to assess the contribution of greenhouse gas emissions generated during the extraction process to global warming. GWP_{20} was applied to evaluate environmental impacts over a 20-year time horizon by estimating emissions of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). All emissions were converted into carbon dioxide equivalents (CO_2e) using Equation (6), based on the guidelines provided in the *Collaboration for Sustainability* report published by (PT PLN, 2023).

$$GWP_{20} = E \times ((EF_{CO2} \times GWP_{CO2}) + (EF_{CH4} \times GWP_{CH4}) + (EF_{NO2} \times GWP_{NO2})) \quad (6)$$

where GWP_{20} is Global Warming Potential for 20 years (kg CO_2e), E is electrical energy (kWh), EF_{CO2} is emission factor CO_2 equivalent 0.85 kg/kWh, EF_{CH4} is emission factor CH_4 equivalent 0.000025 kg/kWh, EF_{NO2} is emission factor N_2O equivalent 0.00002 kg/kWh, GWP_{CO2} is global warming potential CO_2 equivalent 1, GWP_{CH4} is global warming potential CH_4 equivalent 85, GWP_{NO2} is global warming potential N_2O equivalent 290.

2.7. Kinetic Approach of Phenolic Compounds during MAE

MAE performance was analyzed using the Peleg kinetic model, which describes the relationship between microwave power, extraction time, and the concentration of dissolved compounds in the liquid extract (Pavlić *et al*., 2023). In this model, B_0 represents the extraction rate constant (mg/mL·min), while C_e denotes the equilibrium capacity constant (mg/mL). For the initial condition $C_0 = 0$, the Peleg model expressed in Equation (7) can be simplified to Equation (8). Equation (8) was used as a predictive model to estimate the total phenolic content (TPC) concentration in the extract during the MAE process (Naik et al., 2022; Zhang et al., 2023).

$$C(t) = C_0 + \frac{t}{\frac{1}{B_0} + \frac{t}{C_e}} \quad (7)$$

$$C(t) = \frac{t}{\frac{1}{B_0} + \frac{t}{C_e}} \quad (8)$$

The predictive performance of the Peleg model was evaluated to estimate phenolic content under different microwave power levels and extraction times. This evaluation was conducted by calculating several statistical parameters to assess the model's goodness of fit to the experimental data.

The sum of squared errors (SSE) measures the total deviation between predicted and experimental values, where lower values indicate better model performance (Equation 9). The root mean square error (RMSE) quantifies the average magnitude of prediction errors (Equation 10). The chi-square (χ^2) statistic evaluates the degree of discrepancy between the model and experimental data (Equation 11). The coefficient of determination (R^2) describes the strength of the relationship between predicted and observed values, with values approaching 1 indicating a strong fit (Equation 12) (Susanti *et al*., 2021 ; Khwaja *et al*., 2020).

$$SSE = \sum_{i=1}^{N} \left(C_{obs,i} - C_{pred,i}\right)^2 \quad (9)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(C_{obs,i} - C_{pred,i}\right)^2} \quad (10)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(C_{obs,i} - C_{pred,i}\right)^2}{N - n} \quad (11)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(C_{obs,i} - C_{pred,i}\right)^2}{\sum_{i=1}^{N}\left(C_{obs,i} - C_{obs}\right)^2} \quad (12)$$

2.8. Statistical Analysis

Each combination of microwave power and extraction time was performed in triplicate. The data were analyzed to determine the effects and interactions of power and time on TPC using two-way analysis of variance (ANOVA) with a significance level of $p < 0.05$ (95% confidence interval) (SPSS version 25.0). When significant differences were detected, Duncan's Multiple Range Test (DMRT) was applied as a post hoc analysis.

The DMRT results were used to classify treatment means into statistically significant groups. Different superscript letters indicate significant differences among treatment groups, with greater differences reflecting stronger statistical effects on the tested variables.

3. RESULTS AND DISCUSSION

3.1. Temperature Profile under Different Microwave Power Levels

Based on the temperature profile results shown in Figure 2, microwave power significantly influenced temperature changes during the MAE process. Real-time temperature monitoring is essential to understand the dynamic effects of power variation on extraction performance and energy efficiency. Increasing microwave power enhances the intensity of energy absorbed by the solvent and cinnamon bark matrix, thereby accelerating the heating rate and leading to higher temperature increases (Vo *et al*., 2023).

The increase in solvent temperature is associated with ion migration and dipole rotation mechanisms, in which the heating rate depends on the dielectric properties of the solvent and its response to microwave energy. At 800 W, the MAE system reached the target temperature within 14 min, indicating rapid microwave energy absorption and efficient heating. At 720 W, the target temperature was achieved in 16 min, whereas at 640 W, it required 22 min. These results demonstrate that microwave heating is faster than conventional heating methods (Samanta & Ghosh, 2023). Higher microwave power accelerates temperature increases, which subsequently enhances the extraction efficiency of phenolic compounds from cinnamon (Wong & Nillian, 2023).

3.2. Temperature Distribution during MAE

The temperature distribution within the extraction system is presented in Figure 3. Microwave power influenced the rate at which the temperature increased toward the target value of 90 °C. The temperature measurements at points T1 and T8 showed only small differences between the ambient temperature and the temperature inside the microwave chamber, indicating relatively uniform heat distribution. The temperature distributions shown in Figures 3 indicate that measurement points T3, T4, and T5 represent the main extraction zones, exhibiting a rapid temperature increase during the initial 0–30 minutes, followed by stabilization until the end of the process. This pattern was consistent across all power levels, indicating that MAE effectively homogenized temperature throughout the solvent and material matrix (Li *et al*., 2021).

At high power (800 W), temperatures at T3–T5 reached their highest values and remained stable, reflecting more intense and uniform absorption of microwave energy. This enhanced heating increased the mass transfer driving force, promoting faster diffusion of phenolic compounds into the solvent and resulting in higher TPC values compared with lower power levels. In addition, at 800 W, measurement point T6, representing the area surrounding the reactor, exhibited higher temperatures than those observed at other power levels, indicating greater heat loss to the environment through convection and radiation (Xiao *et al*., 2021). Although stable high temperatures at T3–T5 supported increased TPC, excessive thermal exposure may accelerate phenolic degradation. Therefore, while high microwave power maximizes TPC yield, it also increases the risk of compound degradation if extraction time is not properly controlled.

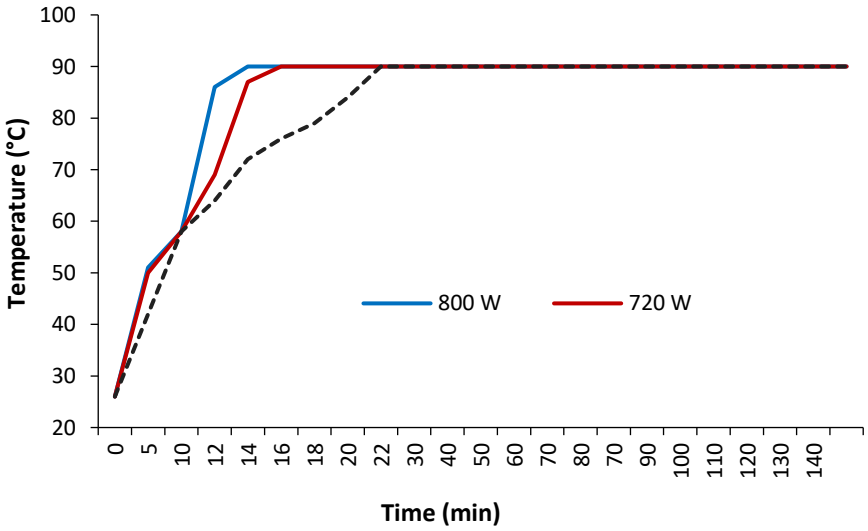


Figure 2. Temperature response to MAE power variation

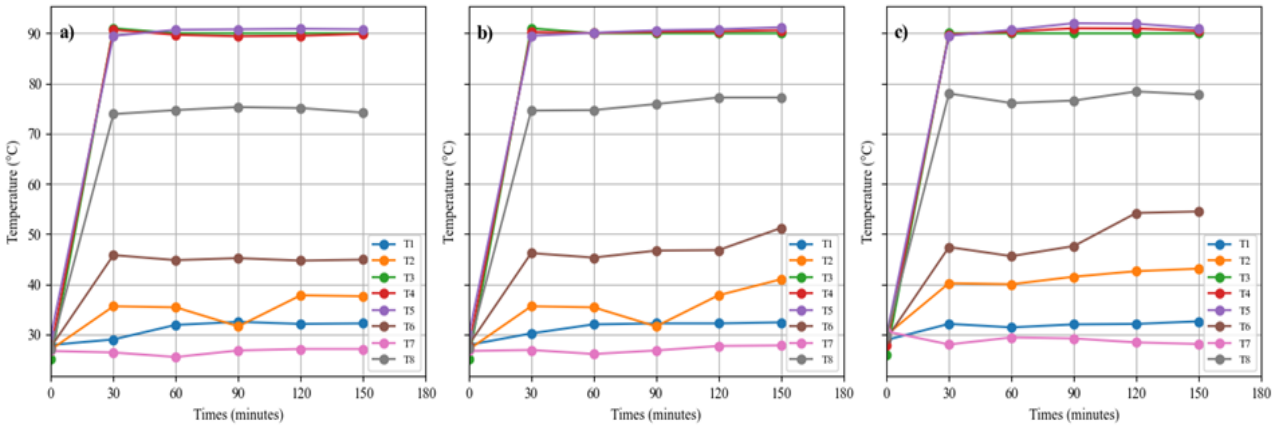


Figure 3. (A) Heat distribution at 640 W of power, (B) Heat distribution at 720 W of power, (C) Heat Distribution at 800 W of Power

3.3. Mass Balance

Power Microwave power is a key parameter influencing temperature variation during the MAE process. Mass and energy balance analyses were conducted comprehensively from the initial stage to the end of extraction for each experimental system. In each extraction system, three main components were considered: mass and energy input (I), mass and energy output as products (A), and mass and energy losses as waste or residues (O).

The output components included extracted solutes, solid residues (dregs), water vapor, and residual solvent. Through mass and energy balance analysis, the extraction efficiency of cinnamon bark can be quantitatively evaluated, providing a comprehensive assessment of active compound recovery. Furthermore, this approach offers a basis for optimizing operational parameters, including temperature, microwave power, solvent-to-material ratio, and extraction time (Hearunyakij & Phutdhawong, 2022).

The amount of water vapor produced is greatly influenced by the amount of heat energy entering the system. Figure 4 shows the first stage in the mass balance analysis, namely the weighing balance. The initial mass of cinnamon bark was recorded at 1009 kg. However, after reweighing using a calibrated analytical balance, the actual mass was obtained at 1002 kg. This accommodation value or difference is equivalent to 0.69 % of the initial mass, which must be taken into account in the mass balance to maintain the overall accuracy of the calculation.

The grinding process was carried out using a grinding machine. The resulting powder consisted of 783 g of fine cinnamon powder, 107.3 g of coarse cinnamon granules, and 118.8 g of cinnamon granule fraction. The data were obtained by measuring the product mass three times after the grinding process. This process was followed by sieving using an 80-mesh sieve to separate the fractions based on particle size. The use of an 80-mesh sieve prevented the coarse particles from being completely filtered, resulting in a significant amount of cinnamon granule fraction.

In the preparation of solvent, NaDES CAS is made through a homogenization process using ultrasonic technology. The components consist of 105.19 g of citric acid, 171.18 g of sucrose, and 500 mL of distilled water. After going through the homogenization process, this mixture produces a NaDES CAS solution with a total mass of 733.18 g. The homogenization process using ultrasonics is carried out in an open system and is sourced from acoustic cavitation energy (Thilakarathna *et al*., 2023). Each variation of microwave power produced a different mass composition in the extraction fraction. The composition of the mass that comes out consists of dissolved substances, solid residue, residual solvents, and water vapor.

Based on Figure 4, the extraction treatment using 800 W power produced the highest percentage of dissolved substances, namely 0.248% w/w, compared to 720 W power of 0.242% and 640 W power of 0.23%. The increase in the amount of solute indicates that the higher the power used, the higher the concentration of phenolic compounds extracted from cinnamon. However, higher power also causes an increase in water vapor production due to the increased heat energy entering the system. This increase was due to the accumulation of greater thermal energy, so that more water evaporated during the process. In the treatment with 800 W of power, the mass of water vapor formed was recorded as the highest, which was 9.241%.

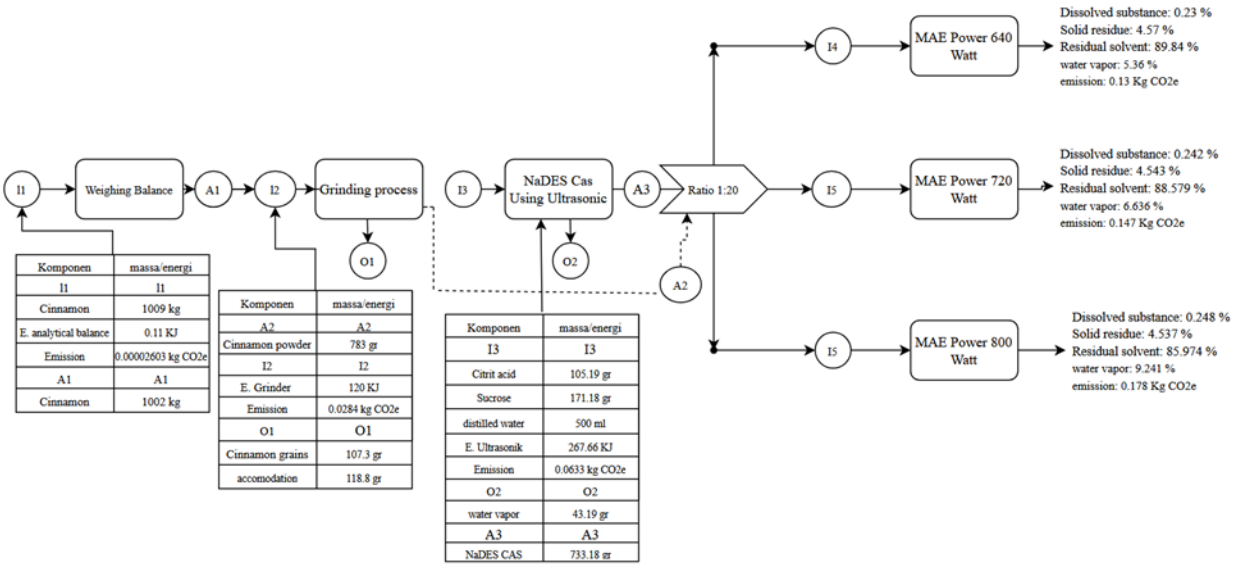


Figure 4. Mass and energy balance of the cinnamon extraction process

3.4. Energy Balance

The ratio of energy output to energy input determines the energy efficiency of the extraction process. High energy consumption can potentially increase greenhouse gas emissions, particularly carbon dioxide (CO_2). These emissions are a major contributor to global warming and climate change (Tanruean *et al*., 2025).

The energy efficiency data presented in Tables 1 and 2 indicate that MAE operated at 640 W exhibited the highest efficiency (69.82%), with an energy loss of 163.21 kJ during the cinnamon extraction process. In contrast, ultrasonic extraction achieved an efficiency of only 52.42%. This difference demonstrates the superior heat transfer performance of MAE compared with ultrasonic-assisted extraction. Microwave heating enables direct energy absorption by polar molecules in the solvent and plant matrix through dipole rotation and ion conduction mechanisms, resulting in

volumetric heat generation throughout the sample. This process minimizes heat loss to the surrounding environment and promotes uniform heating. Conversely, ultrasonic extraction relies primarily on heat transfer through conduction and convection from the container wall to the solvent, which often leads to less homogeneous temperature distribution and lower heat transfer efficiency.

Table 1. Energy requirements during preparation process

Process Name	Energy in (kJ)	Energy out (kJ)	Loss Energy (kJ)	Efficiency (%)
Weighing balance	0.12	0.0715	0.0485	59.58
Grinding Process	120	102.86	17.14	85.72
Ultrasonic solvent preparation 1	274.48	143.89	130.59	52.42
Ultrasonic solvent preparation 2	260.84	131.05	129.79	50.24

Table 2. Energy requirements data on MAE

Process Name (W)	Energy in (kJ)	Energy out (kJ)	Loss Energy (kJ)	Efficiency (%)
MAE 640	540.86	377.64	163.21	69.82
MAE 720	614.74	405.59	209.16	65.98
MAE 800	743.55	460.61	282.94	61.95

Analysis of MAE power variation efficiency indicates that higher efficiency is inversely related to energy loss (Mao *et al*., 2021), suggesting that input energy is more effectively utilized to increase temperature and enhance extraction performance. In this study, operation at 800 W resulted in the lowest efficiency (61.95%) and the highest energy loss (282.94 kJ). These differences in energy requirements are associated with the energy absorption characteristics of the material and solvent. At higher microwave power, the temperature increases more rapidly, leading to a shorter effective heating period. However, excess unabsorbed energy is dissipated to the surrounding environment in the form of latent heat and radiation, thereby reducing overall energy efficiency (Shihong *et al*., 2020).

3.5. Impact of Electricity-Related Emissions on Global Warming Potential during Extraction

Electricity consumption from the PLN grid significantly contributes to greenhouse gas emissions that affect Global Warming Potential (GWP). In Indonesia, most electricity is still generated from fossil fuels, particularly coal. The combustion of these fuels releases substantial amounts of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrogen oxides (NO_x), which contribute to global warming.

The calculated greenhouse gas emissions, expressed as carbon dioxide equivalents (CO_2e), indicate that emissions increased with higher electrical power during the cinnamon extraction process. As shown in Table 3, operation at 800 W resulted in the highest emissions (0.1797 kg CO_2e), followed by 720 W (0.1490 kg CO_2e) and 640 W (0.1314 kg CO_2e). These results demonstrate a positive relationship between electricity consumption and greenhouse gas emissions.

Higher energy consumption leads to increased emissions, thereby contributing to greater global warming potential. Given that global greenhouse gas emissions are approaching critical levels, even modest reductions in emissions are considered environmentally significant. In this context, compared with conventional extraction methods, MAE exhibits lower environmental emission levels, highlighting its potential as a more sustainable extraction technology (Sai-Ut *et al*., 2024).

Table 3. CO_2 emissions per production cycle of cinnamon extract

Power (W)	Weighing balance (kg CO_2e)	Grinder Emission (kg CO_2e)	Ultrasonic Emission (kg CO_2e)	Emission MAE (kg CO_2e)	Total Emissions (kg CO_2e)
640				0.1288	0.131
720	0.000026	0.0284	0.01266	0.1465	0.140
800				0.1771	0.179

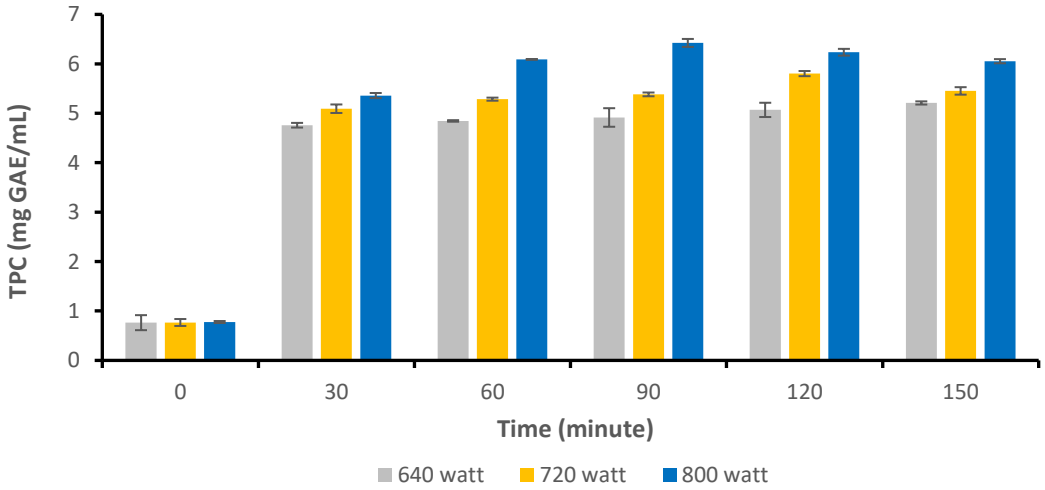


Figure 5. Effect of microwave power on TPC during MAE

3.6. Effect of MAE Power on TPC Enhancement

Microwaves Microwave energy generated during MAE can rapidly and uniformly penetrate plant cell tissues, leading to cell wall disruption and enhanced release of phenolic compounds into the extraction solvent (Tsiaka *et al*., 2023). This mechanism accelerates mass transfer and improves extraction efficiency. As shown in Figure 5, MAE follows the fundamental principles of diffusion-based extraction, in which phenolic yield increases at optimal temperatures while requiring shorter extraction times. In this study, TPC values ranged from 0.76 to 6.42 mg GAE/mL, using gallic acid as the standard reference (Izza *et al*., 2023). These values are higher than those reported by Jouki *et al*. (2021), indicating the superior extraction performance of the MAE method under the applied conditions.

As shown in Table 4, no significant differences in TPC were observed between 30 and 60 min of extraction. However, at longer extraction times (90–150 min), the differences in TPC among power levels became more pronounced, indicating that higher microwave power significantly influences phenolic extraction. This effect is attributed to the ability of microwave energy to disrupt cinnamon cell walls, thereby facilitating the diffusion of bioactive compounds into the solvent. The highest TPC value (6.42 mg GAE/mL) was obtained at 800 W. Nevertheless, prolonged extraction time and excessive microwave power may lead to a reduction in TPC (Oufighou *et al*., 2025; Hernandez *et al*., 2023). These conditions can cause structural degradation of phenolic compounds, resulting in decreased concentrations. In this study, such reductions were observed at 720 W for 120 minutes and at 800 W for 120 and 150 minutes. This finding is consistent with the results reported by Anis & Ahmed (2023), who demonstrated that microwave power above 500 W combined with extended extraction time can reduce TPC levels.

This test was conducted to determine significant differences among the compared treatment groups. The similar DMRT values observed at 640 W and 720 W indicate that increasing power within this range did not produce a statistically significant additional effect on TPC. This phenomenon may be attributed to energy saturation, data variability, limited parameter sensitivity, or incomplete energy absorption by the sample. In contrast, for the 800 W

Table 4. TPC values (mg GAE/mL) at different microwave power levels and their DMRT analysis

Time (minutes)	640 W	720 W	800 W
0	0.76 ± 0.087^{a}	0.768 ± 0.04^{a}	0.77 ± 0.011^{a}
30	4.75 ± 0.02^{b}	5.09 ± 0.049^{d}	5.35 ± 0.029^{fg}
60	4.84 ± 0.008^{bc}	5.28 ± 0.017^{ef}	6.08 ± 0.003^{i}
90	4.91 ± 0.108^{c}	5.38 ± 0.02^{fg}	6.42 ± 0.046^{k}
120	5.06 ± 0.083^{d}	5.80 ± 0.03^{h}	6.23 ± 0.039^{j}
150	5.2 ± 0.018^{de}	5.45 ± 0.043^{g}	6.05 ± 0.024^{i}

Note: Numbers followed by different letters in the same row indicate significant differences based on the DMRT at $\alpha = 0.05$.

treatment consistently exhibited distinct superscript letters across all extraction times. This result suggests that the energy absorbed by the sample exceeded the saturation threshold, thereby accelerating mass transfer and improving thermal efficiency, which significantly influenced TPC values. Variations in superscript letters indicate statistically significant differences among treatments, confirming that the combined effects of increased microwave power and extraction time contributed substantially to TPC enhancement.

3.7. Performance of the Peleg Model in Predicting TPC during MAE

A kinetic modeling approach was applied to evaluate changes in TPC during cinnamon extraction under different microwave power levels using the Peleg model. Data fitting analysis was performed to assess model suitability based on statistical parameters, including SSE, RMSE, χ^2, and R^2. As shown in Table 5, the extraction rate constant (B_0) decreased with increasing microwave power, from 0.2117 at 640 W to 0.1341 at 800 W. High microwave power can induce a rapid increase in system temperature, which may cause thermal degradation of phenolic compounds and reduce the stability of the NaDES-CAS solvent (Mao et al., 2021). These effects may inhibit mass transfer efficiency during the initial extraction stage, thereby contributing to a reduction in the extraction rate constant. Therefore, high microwave power is effective only when combined with an appropriate extraction time (Sai-Ut et al., 2024).

In contrast, the equilibrium capacity constant (C_e) presented in Table 5 exhibited a positive correlation with increasing power, rising from 0.5675 to 0.6982 mg/mL. This parameter reflects the capacity of the NaDES-CAS solvent to accommodate extracted phenolic compounds at equilibrium. The positive synergistic effect between NaDES-CAS and microwave irradiation enhances compound release by disrupting the structural integrity of the sample matrix. Consistent with the findings of Izza et al. (2023), C_e increased with higher applied power.

Table 5. The kinetic parameters of the Peleg model

Power (W)	B_0 (mg /mL.min)	C_e (mg /mL)	SSE	RMSE	χ^2	R^2
640	0.2117	0.5676	0.0006	0.0136	0.0002	0.9973
720	0.2095	0.5828	0.0008	0.0154	0.0003	0.9971
800	0.1341	0.6982	0.0011	0.0190	0.0004	0.9969

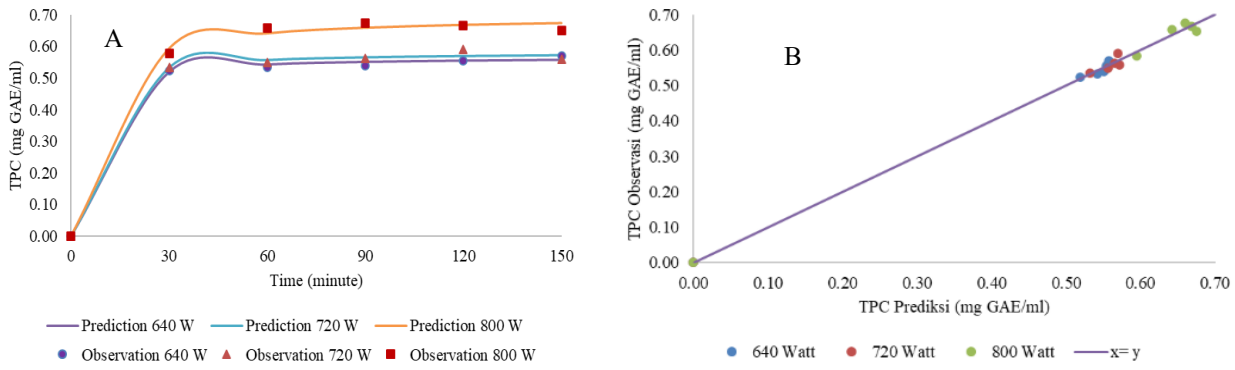


Figure 6. (A) Predicted and observed TPC values of cinnamon bark extract based on microwave power and extraction time, and (B) Observation vs. predictions results using the Peleg model

The Peleg model demonstrated good predictive accuracy, as indicated by low SSE, RMSE, and χ^2 values and R^2 values approaching unity. These results confirm the reliability of the model in describing the extraction kinetics of phenolic compounds under various power and time conditions. The relationship between predicted and observed TPC values over time is illustrated in Figure 6A. The predicted curve closely follows the experimental data, indicating strong agreement between model predictions and observed values. This similarity in curve patterns demonstrates that the Peleg model accurately describes the dynamics of phenolic compound extraction throughout the extraction process. Moreover, it confirms the reliability of the model in predicting TPC kinetics under different operating conditions.

Figure 6B further supports this finding, showing that most data points are closely distributed along the reference line (X = Y). This alignment indicates high predictive accuracy of the Peleg model. The linearity between predicted and observed values reflects the model's ability to represent proportional trends in TPC variation. The closer the data points are to the X = Y line, the smaller the deviation between predictions and observations, confirming the model's consistent performance across the entire data range.

4. CONCLUSION

Variation in MAE power (640, 720, and 800 W) significantly influenced temperature profiles, kinetic behavior, and extraction efficiency. Operation at 640 W achieved the highest thermal efficiency (69.82%) with moderate TPC, whereas 800 W produced the highest TPC value (6.42±0.046 mg GAE/mL) due to enhanced microwave energy transfer and improved mass transfer. However, excessive power combined with prolonged extraction time promoted degradation of bioactive compounds, resulting in reduced extraction effectiveness. Therefore, optimal TPC recovery can be achieved by balancing high microwave power with appropriate extraction duration to maximize phenolic yield while minimizing thermal degradation. These findings highlight the potential of MAE combined with NaDES as an efficient and sustainable approach for cinnamon phenolic extraction.

AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
NA	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			
DYS	✓	✓			✓	✓		✓		✓	✓		✓	✓
MPK			✓	✓			✓		✓	✓	✓	✓		

C: Conceptualization
M: Methodology
So: Software
Va: Validation
Fo: Formal Analysis
I: Investigation
D: Data Curation
R: Resources
O: Writing - Original Draft
E: Writing - Review & Editing
Vi: Visualization
Su: Supervision
Fu: Funding Acquisition
P: Project Administration

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