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Research Article

Multi-Objective Optimization of Solvent-Free Microwave Extraction vs. Microwave Hydrodiffusion and Gravity for *Amomum compactum* Essential Oil

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Abstract
Amomum compactum essential oil, rich in 1,8-cineole (55–70%), is valued for its therapeutic and aromatic properties but suffers from low yield and thermal degradation in conventional extraction. This study compares and optimizes two green, solvent-free microwave-assisted methods—solvent-free microwave extraction (SFME) and microwave hydrodiffusion and gravity (MHG)—using Box–Behnken Design (BBD) under response surface methodology (RSM). Process variables included feed-to-distiller (F/D) ratio (0.10–0.20 g/mL), microwave power (150–450 W), and extraction time (60–90 min). SFME achieved the highest yield (5.25%) at 300 W, 0.15 g/mL, and 75 min, whereas MHG yielded 2.50% at 150 W, 0.10 g/mL, and 90 min, with superior 1,8-cineole recovery (59.65%) and linalool content (1.98%). Both methods reduced extraction time by 85–95% and energy use by over 90% compared with hydrodistillation, consuming only 0.004–0.006 kWh/g. SEM results confirmed extensive gland rupture (80–90%) and structural breakdown supporting enhanced mass transfer. These findings highlight SFME and MHG as sustainable, energy-efficient innovations aligning with SDGs 9, 12, and 13, advancing the circular bioeconomy and scalable green production of *Amomum compactum* essential oil.

Keywords: *Amomum compactum*, box–behnken design, essential oil, innovation, microwave hydrodiffusion and gravity, solvent-free microwave extraction

1. INTRODUCTION

Indonesia, as an agrarian nation, relies heavily on its agricultural sector, which plays a vital role in the national economy. The country's abundant natural resources and fertile land offer considerable potential for agricultural development, thereby enhancing export performance and contributing significantly to economic growth. Among Indonesia's key agricultural commodities, spices such as nutmeg, cloves, and cardamom hold a competitive advantage in the global market [1][2]. Cardamom (*Amomum compactum*) is a major spice cultivated in Indonesia, particularly in Lampung Province, and is recognized for its valuable essential oil, which exhibits antioxidant, antimicrobial, and anti-inflammatory activities [3]-[5]. The oil's key bioactive constituents, notably 1,8-cineole, linalool, and terpinyl acetate, have applications in perfumery, food flavoring, and natural medicine, establishing *Amomum compactum* as one of Indonesia's most commercially significant spice plants [6][7].

However, traditional extraction techniques such as hydrodistillation (HD), steam distillation (SD), and solvent extraction (SE) face critical limitations, including long processing times, high energy and water consumption, and thermal degradation of volatile compounds [8][9]. These methods also pose environmental concerns due to solvent residues and substantial carbon emissions [10][11]. As global industries transition toward sustainable and circular production systems, the development of green extraction technologies becomes imperative to enhance efficiency while minimizing environmental impact [12]-[14].

Microwave-assisted extraction (MAE) represents one of the most promising green extraction techniques, characterized by volumetric dielectric heating that promotes rapid cell rupture and efficient release of volatile compounds [8][15]-[18]. Recent innovations have led to solvent-free microwave extraction (SFME) and microwave hydrodiffusion and gravity (MHG) as advanced, eco-efficient variants of MAE, which operate without solvents and at lower temperatures, thus preserving the integrity of thermolabile components

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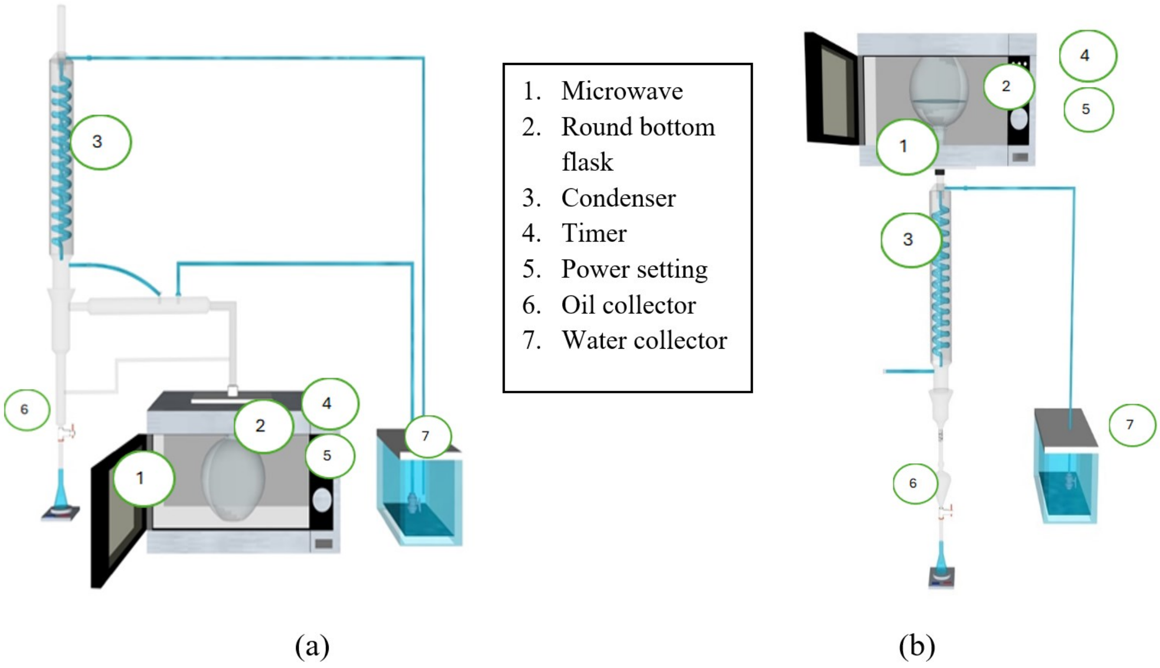


Figure 1. Schematic representation of the MAE apparatus: (a) SFME and (b) MHG.

[19]-[22]. Studies have shown that SFME can yield higher oil recovery in shorter times compared to hydrodistillation, while MHG ensures superior product quality with minimal thermal degradation [23]-[25].

Further refinement of MAE has led to the development of solvent-free microwave extraction (SFME) and MHG as cleaner, greener alternatives for essential oil recovery. These solventless methods eliminate the need for external solvents and operate at lower temperatures, thereby conserving energy and preserving the integrity of volatile components [26]-[28]. Empirical studies have demonstrated that SFME can yield higher amounts of oil compared to conventional HD, while reducing extraction time and minimizing thermal degradation [29][30]. Likewise, MHG has been reported to produce superior yields and chemical profiles while operating under mild thermal conditions [31][32].

Despite extensive studies on SFME and MHG for various aromatic plants, their application to *Amomum compactum* remains limited. Given that its essential oil is rich in 1,8-cineole—a compound with antimicrobial, antiviral, and respiratory therapeutic potential [33]-[35]. It is crucial to establish an optimized and sustainable extraction process for this species. Furthermore, limited research has applied rigorous statistical modeling to optimize *Amomum compactum* extraction, highlighting a gap in understanding the influence of operational parameters on yield and energy efficiency [36]-[38].

To address this gap, the present study employs response surface methodology (RSM) with Box–Behnken Design (BBD) to optimize key variables—microwave power, extraction time, and feed-to-distiller ratio (F/D)—in both SFME and MHG systems. RSM–BBD provides a systematic approach to model nonlinear interactions between variables, reduce experimental runs, and identify optimal operating conditions trials [39]-[41]. This design framework has been successfully applied in optimizing essential oil extraction from other *Zingiberaceae* species, such as *Kaempferia galanga* and *Cinnamomum camphora*, but has not yet been reported for *Ammomum compactum* [42]-[44].

The primary objectives of this research are threefold: (i) to compare the extraction performance of SFME and MHG for *A. compactum* essential oil, (ii) to optimize process parameters using BBD under RSM, and (iii) to analyze the physicochemical and compositional characteristics of the extracted oils via GC–MS and SEM. By integrating solvent-free extraction with statistical optimization, this work proposes a green and energy

-efficient approach for sustainable essential oil production. The study not only supports Indonesia's spice industry development but also contributes to the implementation of SDG 12 (responsible consumption and production) and SDG 13 (climate action) through low-emission processing pathways [45].

2. MATERIALS AND METHODS

2.1. Materials

Fresh *Amomum compactum* fruits were obtained from Lampung Province, Indonesia, and authenticated by the Indonesian Institute of Sciences (LIPI). The samples were cleaned, air-dried for 72 h at ambient temperature (25–28 °C), and then stored in airtight containers to prevent moisture absorption. The moisture content of the raw material was determined gravimetrically using an oven at 105 °C for 3 h. All reagents used were of analytical grade and purchased from Merck (Germany). The composition and physical characteristics of *Amomum compactum* have been previously reported to vary depending on environmental and postharvest conditions activities [3]-[5].

Before extraction, the dried fruits were finely ground using a mechanical disk mill to achieve uniform particle size of approximately 5 mm. This size reduction step was critical to increase the surface area, thereby enhancing the efficiency of microwave-based extraction processes. Anhydrous sodium sulfate (Na_2SO_4), obtained from PT. Bratacco (Surabaya, Indonesia), was used as a desiccant to remove residual water from the collected essential oils post-extraction. No organic solvents were employed during the process to ensure compliance with green extraction principles and to prevent chemical contamination of the product.

2.2. Experimental Procedures

2.2.1. Equipment Setup

The extraction was conducted using a modified household microwave oven (Model EMM2308X, Electrolux) with a maximum power output of 800 W operating at 2.45 GHz. The apparatus was adapted for laboratory-scale essential oil extraction by integrating a 1000 mL round-bottom flask, a Clevenger-type apparatus, Liebig condenser, thermometer, and separatory funnel. The moisture present in the plant acted as an intrinsic heating medium, absorbing microwave energy to generate internal vapor pressure and drive essential oil release [46][47]. This setup was designed to accommodate both SFME and MHG methods.

For SFME, the plant material was placed directly into the round-bottom flask without any added solvent. Microwave irradiation caused cell rupture and vaporization of volatile components, which were subsequently condensed and separated in the Clevenger apparatus. In the MHG configuration, the sample was arranged vertically in a microwave vessel without immersion in water. Internal moisture within the plant matrix drove the hydrodiffusion process. As vapor was released, it moved upward to the condenser and was collected in a glass trap using gravitational flow. The schematic representation of the MAE system for both SFME and MHG is shown in Figure 1.

2.2.2. SFME

The experiments were conducted at microwave powers of 300–600 W and extraction times ranging from 1 to 3 h. Condensed vapors were separated into oil and water layers by decantation, and the essential oil yield (Y, %) was calculated based on the dry mass of the sample. The operational mechanism of SFME is based on volumetric dielectric heating, which ensures rapid and uniform

Table 1. Factors and levels used for optimization in Box Behnken Design.

Factors	Unit	Symbols	Levels		
			Low (-1)	Medium (0)	High (+1)
Microwave Power	W	A	150	300	450
F/D ratio	g/mL	B	0.10	0.15	0.20
Extraction time	Min	C	60	75	90

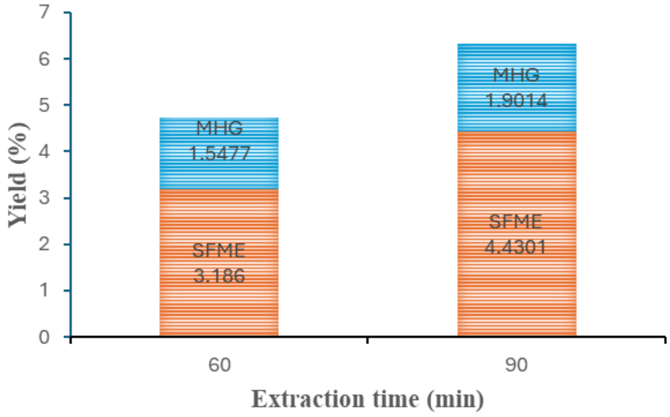


Figure 2. Comparison of extraction time performance on yield between SFME and MHG (F/D ratio 0.1 g/mL, microwave power 300 W, and extraction time 60 and 90 minutes).

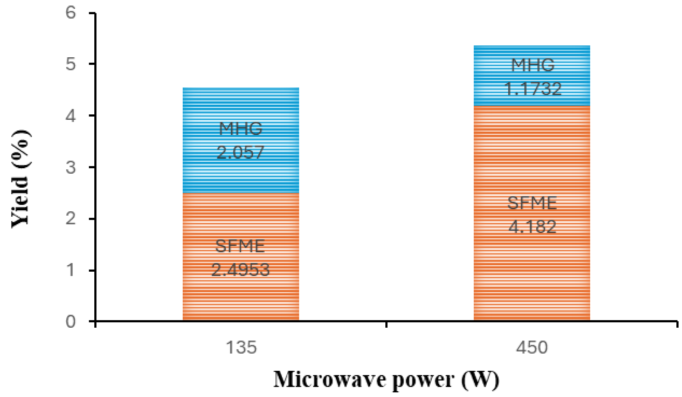


Figure 3. Comparison of the effect of microwave power on yield between SFME and MHG (F/D ratio 0.15 g/mL, extraction time 60 minutes, and microwave power 150 and 450 W).

temperature distribution while minimizing thermal degradation of volatile compounds [10][19][48]. The dried oil was stored in amber vials at 4 °C for further analysis. Each extraction condition was repeated in triplicate to ensure reproducibility.

2.2.3. MHG

The MHG method was performed using a similar microwave system but in an open configuration that allowed the vaporized essential oil and moisture to migrate upward through a condenser and collect by gravity [32][49]. In this setup, no external solvent or water was added. The process combines hydrodiffusion and microwave-driven evaporation, leading to a rapid separation of essential oils under mild thermal conditions [20][50].The MHG process was optimized by varying the feed-to-distiller ratio (0.1–0.3 g/mL), microwave power (300–600 W), and extraction time (1–3 h). Compared to hydrodistillation, MHG offers shorter extraction times, higher energy efficiency, and improved oil quality due to reduced oxidation and hydrolysis [32][51].

2.2.4. Determination of Oil Yield

The essential oil yield was calculated using the following Equation (1).

$$\text{Yield (\%)} = \left(\frac{\text{mass of essential oil (g)}}{\text{mass of dry plant material (g)}}\right) \times 100\% \qquad (1)$$

Each run was performed in triplicate, and the results were expressed as mean ± standard deviation (SD).

2.3. Design of Experiment

To optimize the operational conditions for both SFME and MHG, the study employed RSM integrated with BBD. The BBD was selected because it requires fewer experimental runs than the central composite design (CCD) for the same number of factors, thus reducing time, material use, and energy consumption [52]. In addition, BBD avoids extreme corner points that may cause operational instability or overheating in microwave systems, making it more suitable for the moderate conditions of essential oil extraction optimization [53][54]. And this statistical approach was chosen for its efficiency in evaluating nonlinear interactions between multiple process variables while minimizing the number of required experimental runs.

The main factors influencing essential oil extraction are extraction time, microwave power, particle size, and feed-to-distiller (F/D) ratio. However, particle size was not selected as an independent variable due to the natural heterogeneity of *A. compactum* seeds, which makes it difficult to achieve uniform and reproducible grinding. Instead, the feed-to-distiller ratio was chosen as a representative variable to control the mass–energy transfer during extraction. This parameter replaces the typical feed-to-solvent ratio used in conventional solvent-based extraction, as the MHG system operates without added solvent [55]. The selected levels for each variable were determined based on preliminary experiments and supported by relevant literature to ensure realistic and scalable operating ranges. The independent variables—microwave power (150, 300, 450 W), F/D ratio (0.10, 0.15, 0.20 g/mL), and extraction time (60, 75, 90 min)—were selected based on both preliminary experiments and prior research experience with similar microwave-assisted extractions. These levels represent realistic operational ranges that balance extraction efficiency and compound stability, ensuring safe operation under moderate microwave energy without overheating or degradation of thermolabile compounds. Three independent variables were selected based on preliminary trials shown in Table 1. Each variable was evaluated at three coded levels (−1, 0, +1), resulting in 15 experimental combinations per method, including three center points to estimate pure error and ensure model reliability.

2.4. Statistical Model for RSM

The second-order polynomial model, commonly applied in RSM, is represented by Equation (2);

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_{iX_i} + \sum_{i=1}^{k} \beta_{iiX_i^2} + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ijX_iX_j} \quad (2)$$

where, Y represents the predicted response, β_0 is the constant regression coefficient, β_i is the linear regression coefficient, β_{ii} is the quadratic regression coefficient, and β_{ij} is the interaction regression coefficient. Meanwhile, x_i and x_j are the coded independent variables representing the experimental parameters. This statistical model enables the evaluation of linear, quadratic, and interaction effects of the independent variables, providing a comprehensive framework for optimizing the

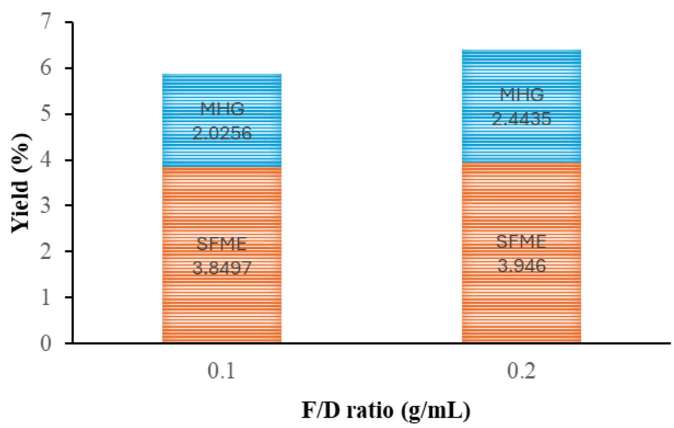


Figure 4. Comparison of the yield to distiller ratio between SFME and MHG (extraction time 75 minutes, microwave power 150 W, and feed to distiller ratio 0.1 and 0.2 g/mL).

Table 2. ANOVA to identify significant factors on SFME.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	7.53	9	0.8372	8.86	0.0135	significant
A-Time	0.3528	1	0.3528	3.74	0.1111	
B-Power	0.5671	1	0.5671	6.00	0.0579	
C-F/S	0.0741	1	0.0741	0.7847	0.4163	
AB	0.7832	1	0.7832	8.29	0.0346	
AC	0.3080	1	0.3080	3.26	0.1308	
BC	0.0400	1	0.0400	0.4235	0.5439	
A^2	2.82	1	2.8200	29.87	0.0028	
B^2	2.94	1	2.9400	31.08	0.0026	
C^2	0.2432	1	0.2432	2.58	0.1694	
Residual	0.4722	5	0.0944			
Lack of Fit	0.4494	3	0.1498	13.10	0.0717	not significant
Pure Error	0.0229	2	0.0114			
Cor Total	8.01	14				

extraction process. The application of RSM facilitated the identification of the most influential parameters and their interactions, ensuring the efficient extraction of high-quality essential oil. Design-Expert version 13.0 (Stat-Ease Inc., USA) and Minitab 21 were used for model development, analysis of variance (ANOVA), and generation of response surface plots. Model adequacy was confirmed using R^2 values, adjusted R^2, lack-of-fit tests, and residual analyses. Optimal conditions were derived by maximizing the desirability function targeting high oil yield and desirable chemical profiles.

2.5. Morphological Analysis

The structural impact of microwave exposure on plant tissues was examined using scanning electron microscopy (SEM). Samples of *A. compactum* were collected before and after extraction, fixed, and coated with a thin layer of gold using a sputter coater. SEM imaging was performed at magnifications ranging from 500× to 5000× using a JEOL JSM-6510LV system. This analysis provided visual evidence of cell wall rupture and oil gland disruption caused by microwave treatment.

2.6. Chemical Composition

Chemical profiling of *A. compactum* essential oils was carried out using gas chromatography–mass spectrometry (GC–MS). The analysis employed an Agilent 7890B GC system coupled with a 5977A mass-selective detector (MSD) and fitted with an HP-5MS capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness). Helium served as the carrier gas at a constant flow rate of 1 mL min^{-1}. The injector temperature was maintained at 250 °C with a split ratio of 10:1. The oven temperature program began at 50 °C (held 2 min), then increased to 250 °C at 4 °C min^{-1}. Compound identification was based on comparison of retention indices and mass spectra with those available in the NIST and Wiley libraries, while relative quantification relied on peak-area normalization [56][57]. Quantitative analysis was based on relative peak areas of key constituents such as 1,8-cineole, linalool, α-terpinene, and β-myrcene.

2.7. Physicochemical Properties

To assess oil quality, the following physicochemical parameters were measured in accordance with AOAC standards refractive index (measured at 25°C using an Abbe refractometer), relative density (determined using a pycnometer at 20 °C), and viscosity (measured with a Brookfield viscometer under controlled temperature conditions). These parameters are important indicators of oil purity, consistency, and potential application in pharmaceutical or cosmetic formulations.

3. RESULTS AND DISCUSSIONS

3.1. Effect of Extraction Parameters

The extraction efficiency of essential oil from *Amomum compactum* was significantly influenced by three critical process parameters—F/D, microwave power, and extraction time. Their effects on yield were analyzed using RSM and visualized through 3D response surface plots to identify individual and synergistic contributions under both SFME and MHG conditions.

3.1.1. Extraction Time

Extraction time exhibited a curvilinear effect on essential oil yield. In both SFME and MHG, the yield increased with extraction duration, peaking between 75 and 80 min before gradually stabilizing. Beyond 90 min, yield either plateaued or declined, indicating potential thermal degradation or volatilization of sensitive compounds. Early in the process, rapid internal heating induces vapor pressure within oil glands, facilitating quick release of volatiles; however, extended exposure may lead to oxidative degradation or secondary reactions among oxygenated terpenes [11][46][58].

Figure 2 shows that at 60 min, SFME achieved 3.19%, while MHG yielded 1.55%, totaling approximately 4.73%. Extending extraction to 90 min increased the total yield to 6.24%, with SFME contributing 4.43% and MHG 1.81%. The ~1.5% gain reflects improved cell rupture and diffusion of trapped volatiles under longer microwave exposure. Similar kinetic trends were reported in microwave extraction of *Cymbopogon citratus* and *Zingiber officinale*, where equilibrium was reached within 70–90 min [10][32].

Prolonged heating beyond this optimum did not proportionally enhance yield due to evaporation losses and the breakdown of thermolabile sesquiterpenes [59][60]. For MHG, the continuous vapor removal mechanism helped maintain lower internal temperature gradients, preventing excessive degradation and allowing slightly better yield stability at extended durations [10][32].

3.1.2. Microwave Power

Figure 3 compares the yield obtained at 150 and 450 W microwave power with an F/D ratio of 0.15 g/mL and an extraction time of 60 min. Microwave power significantly influenced the rate and extent of essential oil recovery. As microwave power increased from 150 to 300 W, yields improved sharply due to enhanced dielectric heating and

Table 3. ANOVA to identify significant factors on MHG.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	13.50	6	2.2500	33.41	< 0.0001	significant
A-Time	0.6692	1	0.6692	9.94	0.0135	
B-Power	7.00	1	7.0000	103.90	< 0.0001	
C-F/S	4.74	1	4.7400	70.43	< 0.0001	
AB	0.0231	1	0.0231	0.3431	0.5742	
AC	0.3162	1	0.3162	4.70	0.0621	
BC	0.7507	1	0.7507	11.15	0.0102	
A^2	0.5387	8	0.0673			
B^2	0.4037	6	0.0673	0.9970	0.5791	not significant
C^2	0.1350	2	0.0675			
Residual	14.04	14				
Lack of Fit	0.7275	3	0.2425	14.81	0.0639	not significant
Pure Error	0.0327	2	0.0164			
Cor Total	12.04	14				

Table 4. Comparative model performance for SFME and MHG extraction methods using BBD.

Statistical Parameter	SFME Model	MHG Model
Model Significance		
F-value	8.86	33.41
p-value	0.0135	<0.0001
Significant Terms	AB, A^2, B^2	A, B, C, BC
Lack-of-Fit Test		
F-value	-	14.81
p-value	0.0717	0.0639
Optimal Conditions		
Time (min)	68.48	72.50
Power (W)	450	359
F/S Ratio	0.150	0.164
Predicted Yield		
Maximum (%)	5.25	2.20
Model Characteristics		
Dominant Effects	Non-linear	Linear
Key Interaction	Time × Power	Power × Ratio
Industrial Applicability	Moderate	High

efficient vaporization of intracellular moisture [11][48]. Beyond 450 W, however, yields declined slightly, indicating overheating and possible degradation of oxygenated monoterpenes such as 1,8-cineole and terpinyl acetate [35][61].

At 150 W, the total oil yield was 4.55%, with SFME and MHG contributing 2.50% and 2.05%, respectively. At 450 W, yield increased to 5.35%, dominated by SFME (4.18%) with a lower contribution from MHG (1.17%). These results confirm that high power levels favor SFME due to more efficient dielectric coupling, whereas excessive energy in MHG can cause volatile loss from uncontrolled vapor flow. Optimal operation was consistently observed near 300 W, where uniform energy absorption minimized hotspots and maximized yield without compromising oil integrity [10].

Similar patterns have been reported for *Kaempferia galanga* and *Curcuma longa* essential oils, where excessive microwave energy led to decarboxylation and isomerization of sesquiterpenes [62]. Thus, careful regulation of microwave power is essential to balance process intensification and compound preservation. This indicates that a higher microwave power significantly boosts the SFME yield but reduces the MHG contribution. The improved SFME efficiency at 450 W may be attributed to greater energy absorption, resulting in faster heating, enhanced breakdown of oil-bearing structures, and improved diffusion. However, the decline in MHG yield at high power suggests potential thermal degradation or excessive vaporization of volatile compounds, emphasizing the need to optimize power settings to balance efficiency and oil quality.

3.1.3. F/D Ratio

The F/D ratio exhibited a nonlinear positive correlation with oil yield up to an optimal threshold. Increasing the F/D ratio from 0.10 to 0.15 g/mL enhanced oil recovery in both systems by improving the density of the absorbing medium within the electromagnetic field, leading to greater energy utilization and efficient cell rupture [46][53]. However, further increasing the ratio to 0.20 g/mL resulted in reduced yield, likely due to nonuniform microwave penetration and reduced vapor diffusion caused by excessive material loading [47][63].

As illustrated in Figure 4, at an F/D ratio of 0.1

g/mL, the total yield reached 5.87% (SFME 3.85%, MHG 2.03%), whereas at 0.2 g/mL, it rose marginally to 6.39% (SFME 3.95%, MHG 2.44%). This plateau effect reflects the trade-off between material loading and energy distribution. Overcrowded biomass can lead to localized heating and vapor entrapment, reducing mass transfer efficiency [59][64]. Comparable findings in *Cinnamomum camphora* and *Amomum subulatum* extractions indicated similar yield saturation beyond optimal biomass loading due to decreased effective diffusivity [65][66]. Hence, maintaining an F/D ratio near 0.15 g/mL is recommended for maximizing yield and ensuring consistent oil quality. Overall, SFME consistently achieved higher and more stable oil yields across all operational parameters than MHG, confirming its superior suitability for process scale-up and industrial integration. These findings align with previous studies emphasizing SFME's potential as an energy-efficient and sustainable green extraction technology [67]-[69], Future research should extend beyond yield optimization to assess compositional fidelity, antioxidant potential, and kinetic modeling of mass-transfer behavior under hybridized SFME–MHG configurations.

3.2. Results Optimization of SFME and MHG Extraction using BBD

The optimization of *A. compactum* seed oil extraction was performed using the SFME method and MHG process, both evaluated through a BBD under RSM. Three independent variables—F/D, microwave power, and extraction time—were investigated for their effects on oil yield. Table 1 presents the factor levels, while Table 2 - 4 summarizes the experimental results, including actual and predicted values with residuals.

3.2.1. Statistical Analysis (ANOVA) of Microwave-Assisted Extraction Models

The ANOVA results for the quadratic model of SFME demonstrated statistical significance (F = 8.86, p = .0135), indicating the model's capability to explain yield variation meaningfully. Significant effects were observed for the time-power interaction (AB) and quadratic terms of time (A^2) and power (B^2) (all $p < .05$), revealing strong non-linear relationships where excessive increases in either parameter led to yield reduction beyond optimal points. In contrast, linear terms for time (A), power (B), feed-to-solvent ratio (C), and interactions AC and BC showed no statistical

Table 5. Comparative predicted values for SFME and MHG extraction methods using BBD.

Run	F/S (g/mL)	Power (W)	Time (min)	SFME		MHG	
				Actual Value	Predicted Value	Actual Value	Predicted Value
1	0.1	300	60	1.55	1.56	0.83	0.85
2	0.1	300	90	2.20	2.57	1.07	0.87
3	0.1	150	75	2.03	1.99	0.38	0.36
4	0.1	450	75	2.17	1.83	1.48	1.36
5	0.15	450	90	0.38	0.35	2.63	2.93
6	0.15	300	75	0.58	0.65	1.44	1.63
7	0.15	150	60	2.16	2.19	0.51	0.48
8	0.15	450	60	1.27	1.60	2.13	2.20
9	0.15	150	90	2.50	2.17	0.70	0.90
10	0.15	300	75	0.58	0.65	1.43	1.63
11	0.15	300	75	0.80	0.65	1.89	1.63
12	0.2	300	90	0.66	0.66	3.36	2.97
13	0.2	150	75	2.44	2.78	0.87	1.03
14	0.2	300	60	3.32	2.95	1.99	1.83
15	0.2	450	75	0.49	0.53	3.71	3.77

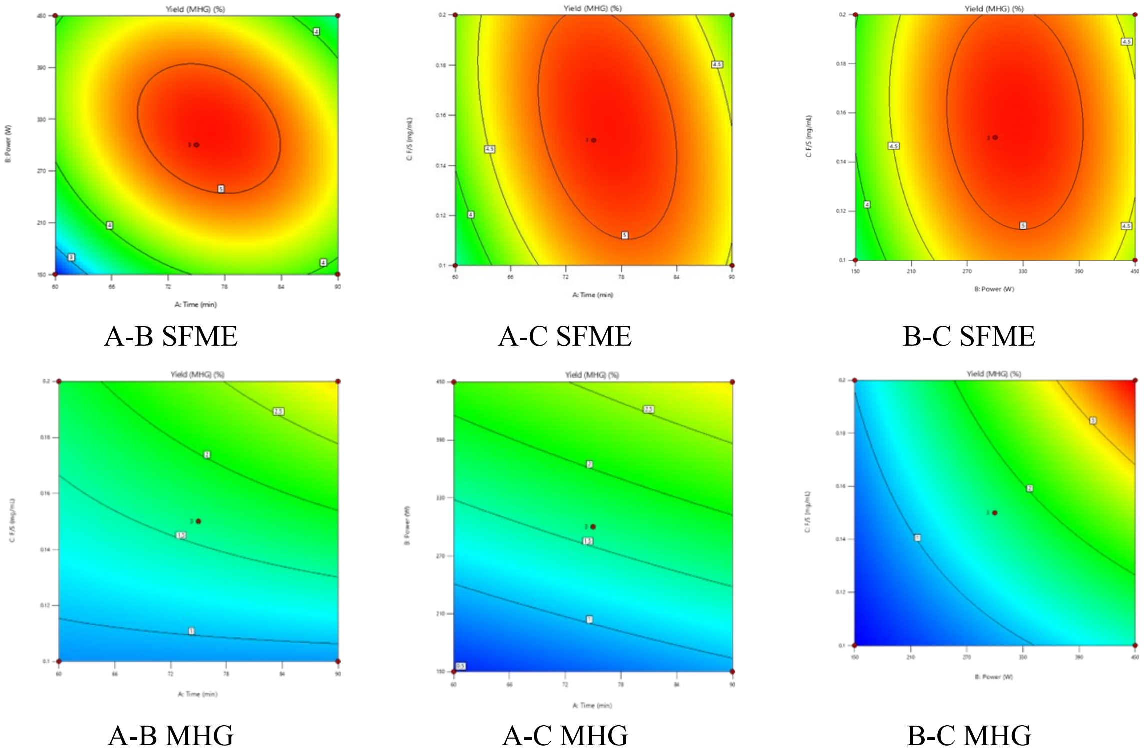


Figure 5. Results of the two-dimensional contour plot analysis on cardamon oil SFME and MHG through the interaction between parameters (a) extraction time with F/D ratio A-C SFME (b) extraction time with microwave power B-C SFME (c) F/D ratio with microwave power A-B SFME, (d) extraction time with F/D ratio A-C MHG (e) extraction time with microwave power B-C MHG (f) F/D ratio with microwave power A-B MHG.

significance ($p > .05$), though they were retained to maintain mathematical hierarchy. The lack-of-fit test ($p = .0717$), while not conventionally significant, suggested potential for model refinement. Nevertheless, the model remains reliable for yield prediction and optimization. Simplification through elimination of non-significant terms may enhance efficiency without compromising predictive accuracy. The quadratic regression model demonstrated good statistical validity, with significant non-linear and interaction components that crucially influence extraction outcomes. These findings suggest that model reduction approaches could be considered while maintaining hierarchical integrity, making this model valuable for both prediction and design of focused subsequent experiments.

For the MHG quadratic model, ANOVA revealed superior statistical significance ($F = 33.41$, $p < 0.0001$), indicating only a 0.01% probability that this F-value occurred by chance. Significant factors affecting yield included extraction time (A, $p = .0135$), microwave power (B, $F = 103.90$, $p < 0.0001$), feed-to-solvent ratio (C, $F = 70.43$, $p < 0.0001$), and the power-ratio interaction (BC, $p = 0.0102$). Notably, power exhibited the strongest influence, followed by feed-to-solvent ratio. The significant BC interaction suggested synergistic effects between these parameters. Other terms (AB, AC interactions and quadratic components A^2, B^2, C^2) showed no significance ($p > 0.05$), indicating limited non-linear effects within the tested parameter space. The non-significant lack-of-fit ($F = 14.81$, $p = 0.0639$) confirmed good model adequacy with no evidence of systematic deviation. This robust model structure, dominated by significant linear terms, could potentially be simplified through elimination of non-significant components without reducing predictive accuracy.

3.2.2. Comparative Model Assessment between SFME and MHG

Comparative analysis revealed three key advantages of the MHG model over SFME :

Statistical Strength: MHG showed substantially higher significance (F = 33.41 vs. 8.86; $p < .0001$ vs. .0135) and predictive power; Parameter Effects: MHG's yield was primarily influenced by linear terms (A, B, C) and one interaction (BC), indicating more straightforward parameter relationships. SFME depended heavily on non-linear components (AB, A^2, B^2), reflecting complex system behavior; Model Fit: While both models passed lack-of-fit tests, MHG demonstrated better alignment ($p = .0639$ vs. .0717) and lower residual error.

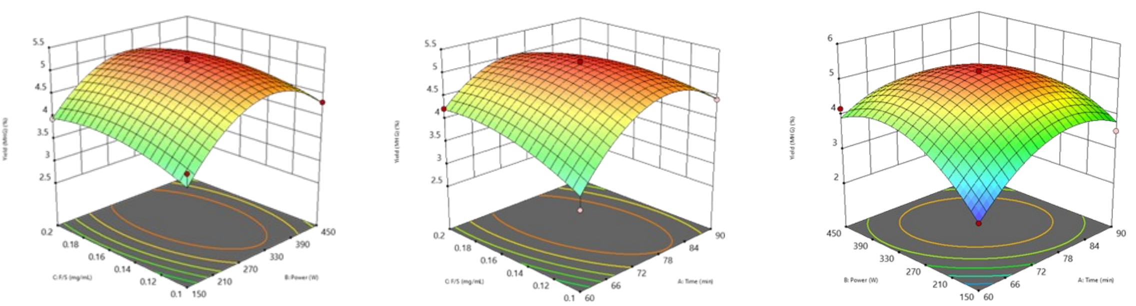
Table 4 compares the model performance of SFME and MHG extraction methods using the Box-Behnken design, while Table 5 illustrates their predicted values. The MHG model's linear-term dominance enhances its suitability for industrial implementation, offering simpler interpretation and more straightforward process control. In contrast, while SFME effectively captures complex nonlinear dynamics, its intricate nature demands more careful parameter optimization. From a practical perspective, MHG's superior statistical robustness, model stability, and fit statistics make it the preferred choice for applications where predictive accuracy and operational efficiency are critical. These findings indicate that although both microwave-assisted extraction methods are viable, MHG is the more reliable option for industrial scale-up and adoption. The differing model behaviors carry significant implications for green extraction technology development. The dominance of linear terms in MHG suggests a more robust process with reduced sensitivity to minor parameter fluctuations—a key advantage in industrial settings. Notably, the synergistic power-ratio interaction (BC) underscores the importance of coordinated parameter adjustments for yield optimization. On the other hand, SFME's prominent nonlinear terms indicate threshold effects, where exceeding optimal time or power levels leads to diminishing returns.

3.2.3. Response Surface and Contour Plot Analysis

The RSM was applied to visualize the influence of key variables on oil yield through both three-dimensional (3D) response plots and two-dimensional (2D) contour plots (Figure 5). These graphical tools aid to identify optimal parameter zones by illustrating the interaction between extraction time, F/D ratio, and microwave power [70][71].

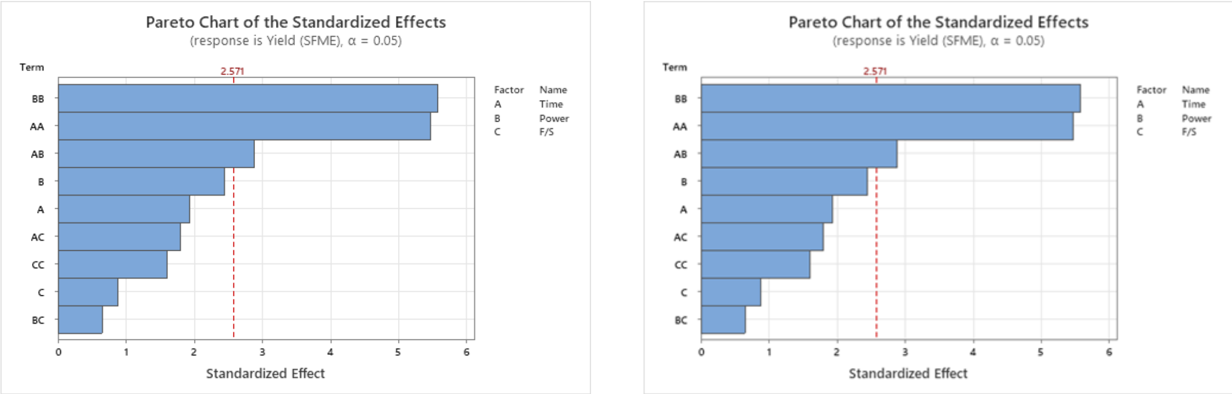
3.2.3.1. Interaction Between Extraction Time and Microwave Power (B–C, SFME)

A pronounced quadratic relationship between microwave power and extraction time was evident. Increasing microwave power initially enhanced yield, but further increases caused a decline, indicating thermal degradation of sensitive volatiles. Similarly, longer extraction times improved yield up to an optimal duration, after which no further benefit was obtained. The central red zone in the contour plot denotes the optimal region, consistent with the ANOVA significance of B^2 and C^2. Comparable nonlinear effects of microwave power and time have been reported for ginger (*Zingiber officinale*) and clove (*Syzygium aromaticum*) essential oils extracted using SFME [66][72][73].



A-B SFME A-C SFME B-C SFME

Figure 6. Results of the response surface plot on cardamon oil SFME through the interaction between parameters (a) extraction time with F/D ratio A-C SFME (b) extraction time with microwave power B-C SFME (c) F/D ratio with microwave power A-B SFME.



(a) (b)

Figure 7. The standardized Pareto charts illustrating the relative effect size of various operational parameters and their interactions on the essential oil yield from *Amomum compactum* using two different extraction methods—SFME (a) and MHG (b).

3.2.3.2. Interaction Between Extraction Time and F/D Ratio (A–C, SFME)

The A–C contour plot (Figures 6(a) – (c)) revealed a parabolic trend, demonstrating that increased extraction time significantly improved yield at lower F/D ratios due to enhanced mass transfer. However, prolonged duration at higher F/D ratios yielded diminishing returns, potentially from overheating and matrix degradation. This aligns with observations from RSM-optimized extractions of Kaempferia galanga and Curcuma longa oils [59][62].

3.2.3.3. Interaction Between F/D Ratio and Microwave Power (A–B, SFME)

A strong elliptical contour indicated a distinct optimum zone, where moderate microwave power coupled with a balanced F/D ratio produced the highest oil recovery. Excessive power decreased yield, whereas low F/D ratios resulted in inefficient energy absorption. This finding corroborates previous studies emphasizing the importance of matrix density and dielectric uniformity in optimizing microwave-based extraction [10][11][68]. For MHG, the response surfaces displayed broader, more linear gradients (Figures 6(d) – (f)), confirming greater process stability and tolerance to parameter variations. The extraction time–power (B–C) interaction demonstrated a steady yield increase without degradation, owing to MHG's built-in moisture regulation that moderates thermal hotspots [32][74]. The F/D–power interaction (A–B) exhibited positive synergy, indicating that increasing both parameters proportionally enhanced yield—a pattern consistent with the significant BC interaction observed in ANOVA. These contour patterns validate the regression results: SFME showed sharp curvature and narrow optimal zones, while MHG demonstrated a smoother response surface and wider operational flexibility. This distinction is critical for process scaling—SFME offers higher selectivity but requires precise control, whereas MHG provides better robustness for continuous extraction [59][64].

3.2.4. Comparative Significance Parameters between SFME and MHG

Figure 7 presents the standardized Pareto charts illustrating the relative effect size of various operational parameters and their interactions on the essential oil yield from *A. compactum* using two different extraction methods—SFME (Figure 7(a)) and MHG (Figure 7(b)). The red vertical line at the threshold value (t = 2.571) indicates the boundary of statistical significance at the 95% confidence level [75][76].

In the SFME method (Figure 7(a)), two quadratic terms, BB (microwave power squared) and AA (extraction time squared), exceeded the significance threshold, identifying them as the most influential variables governing the yield. This finding confirms the model's strong non-linear behavior, where both time and power have optimal ranges beyond which further increases lead to declining efficiency, likely due to thermal degradation or matrix breakdown. The AB interaction (time × power) also exhibited a notable standardized effect, though slightly below the threshold, suggesting that the combination of extended time and high power may produce antagonistic outcomes. Meanwhile, linear effects (B, A, C) and other interactions (AC, BC) remained below significance, albeit still contributing moderately to the model's predictive capability. In contrast, the MHG method (Figure 7(b)) showed a similar trend. Again, BB and AA appeared as the dominant factors, both surpassing the statistical threshold. However, in MHG, the interaction term AB showed a more modest influence, and no other effects exceeded the threshold. These results imply that while non-linear effects are also present in MHG, they may be less critical to operational robustness compared to SFME. Importantly, linear terms (power, time, F/D ratio) remain below the significance line, reinforcing the finding that MHG operates effectively over a broader, more forgiving parameter range. Together, both diagrams emphasize the fundamental difference between the two methods. SFME is more sensitive to precise parameter control due to its high reliance on quadratic effects and interaction terms. MHG, although showing similar dominant factors, demonstrates a more stable performance profile with reduced dependence on interaction variability. These findings align with earlier ANOVA results and support the conclusion that SFME demands more rigorous optimization for maximum yield, while MHG offers greater operational flexibility and scalability.

3.2.4.1. Comparative Model Assessment

Comparing both methods, MHG demonstrated higher overall model strength ($F = 33.41$, $p < .0001$) than SFME ($F = 8.86$, $p = .0135$), confirming superior statistical robustness and predictive reliability. While SFME effectively captures nonlinear phenomena, its sensitivity limits process flexibility. MHG, governed primarily by linear relationships, is more adaptable to industrial-scale operation [68][77]. These findings suggest that SFME offers precision and selectivity ideal for small-batch, high-purity extraction, whereas MHG provides robustness and energy efficiency suitable for continuous or commercial applications. The comparative optimization results align with broader literature on green process intensification and circular bioeconomy frameworks, where scalable, solvent-free, and energy-efficient operations are prioritized [77][78].

3.2.5. Comparative Analysis of Optimization Equations

The RSM yielded the following regression equation for predicting cardamom oil extraction yield (%) as a function of feed-to-distiller ratio (A), microwave power (B), and extraction time (C). Final equation in terms of coded factors.

$$\text{Yield (SFME)} = +5.18 + 0.2100\,A + 0.2662\,B + 0.0962\,C - 0.4425\,AB - 0.2775\,AC - 0.1000\,BC - 0.8742\,A^2 - 0.8917\,B^2 - 0.2567\,C^2$$

$$\text{Yield (MHG)} = +1.63 + 0.2892\,A + 0.9352\,B + 0.7700\,C + 0.0760\,AB + 0.2812\,AC + 0.4332\,BC$$

The SFME equation exhibits strong curvature effects (negative quadratic coefficients), indicating that yield optimization requires careful control of both time and power. The significant negative AB interaction reflects potential antagonism between excessive exposure and power, leading to volatile degradation [79]. In contrast, the MHG model displays a linear-dominant structure with positive BC synergy, reflecting predictable, scalable performance [80][81]. The optimization equation for SFME displays a system highly influenced by non-linear effects. This is evident in the strong quadratic terms, particularly $A^2 = -0.8742$ and $B^2 = -0.8917$, which highlight significant curvature in the response surface. These negative coefficients indicate that both extraction time and microwave power must be controlled carefully to avoid falling outside narrow optimal zones, where excessive input leads to a decline in yield. Additionally, the interaction term AB = -0.4425 reflects antagonistic behavior, where simultaneous increases in both time and power beyond their optimal levels reduce performance. Although the linear coefficient for power = +0.2662 suggests it has the highest individual impact among the linear terms, its influence is still dominated by the curvature effects. The SFME model therefore requires fine-tuned optimization, making it more suitable for small-scale or precision applications where selectivity is prioritized over operational robustness.

In contrast, the MHG equation exhibits a more straightforward, linear-driven system. The linear terms B = +0.9352 and C = +0.7700 show strong positive influence, suggesting that increasing power and feed-to-solvent ratio continuously improves yield within the studied design space. The absence of significant quadratic terms implies that no major curvature is observed, meaning that the process behaves more predictably and can tolerate broader parameter ranges. Moreover, the BC = +0.4332 interaction term reflects synergistic behavior, where the simultaneous increase in power and solvent ratio enhances extraction efficiency. This linearity simplifies control and makes the MHG system inherently more scalable for industrial applications.

From a practical standpoint (Table 6), the SFME model presents challenges for scale-up due to its sensitivity to parameter variation and narrow optimal operating zones. Its baseline yield is higher (intercept = 5.18%), but this advantage is difficult to maintain under dynamic conditions. Meanwhile, MHG offers lower initial yield (intercept = 1.63%), but the strong linear coefficients for B and C make it more suitable for robust, repeatable operation. This makes MHG a preferred option for large-scale extraction processes, especially where solvent use can be adjusted freely and energy input is scalable. Theoretically, the SFME system reflects the characteristics of energy-intensive extraction, where overheating and compound degradation are key limitations. MHG, on the other hand, aligns with mass-transfer-limited systems, where increased driving forces—such as power and solvent ratio—consistently promote better yields. Thus, selection of the method should consider whether process precision (SFME) or operational resilience (MHG) is more aligned with the intended application.

The structure of the optimization equations clearly indicates that MHG's linear-response behavior provides greater operational flexibility and scalability, making it highly suitable for industrial settings. In contrast, SFME's non-linear dynamics, while more complex, may offer superior selectivity and control for specialized extractions. Researchers and process engineers should carefully align method selection with specific process goals—whether prioritizing yield stability and scalability (MHG) or compound selectivity and control (SFME).

3.3. Chemical Composition Analysis

The resulting chromatographic profiles revealed that 1,8-cineole was the most abundant constituent (57.91%), followed by 6,6-dimethyl-2-methylene-bicyclo[3.1.1]heptane (21.53%), (1*R*)-2,6,6-trimethylbicyclo[3.1.1]hept-2-ene (7.17%), β-myrcene (2.90%), γ-terpinene (2.06%), linalool (1.24%), and α,α,4-trimethyl-3-cyclohexene-1-methanol (3.25%). Among these, 1,8-cineole is widely recognized for its antimicrobial, anti-inflammatory, and antioxidant properties [5][82]. The high proportion of 1,8-cineole in *A. compactum* oil supports its use in pharmaceutical, aromatherapeutic, and respiratory-care applications [83]-[85].

Comparative analysis between SFME and MHG extracts revealed differences in volatile-compound distribution (Tables 7 and 8). The SFME method produced a higher proportion of monoterpene hydrocarbons such as bicyclo[3.1.1]heptane (21.53%) compared with MHG (13.94%), reflecting stronger volatilization effects under direct dielectric heating [32][86]. In contrast, MHG favored the preservation of oxygenated terpenes due to the

Table 6. Comparative summary of SFME vs. MHG optimization equations.

Feature	SFME	MHG
Dominant Effects	Quadratic (A^2, B^2)	Linear (B, C)
Key Interaction	AB (antagonistic)	BC (synergistic)
Sensitivity	High (narrow optimum)	Low (broad optimum)
Industrial Scalability	Challenging	Favorable
Predicted Yield (baseline)	5.18%	1.63%
Process Behavior	Energy-sensitive, degradation-prone	Mass-transfer driven, scalable
Best Use Case	Precision, selective extraction	Industrial-scale, robust operation

Table 7. The compositions of cardamom essential oil using SFME.

Peak Numb.	Compund	R.T (min)	Area (%)
	Monoterpen:		
1	2-Methyl-5-(1-methyl)bicyclo[3.1.0]hex-2-ene	6.875	0.23
2	6,6-Dimethyl-2-methylenebicyclo[3.1.1]heptane	8.630	21.53
3	β-Myrcene	9.271	2.90
4	3,7-Dimethyl-(Z)-1,3,6-octatriene	11.349	0.43
5	γ-Terpinene	11.647	2.06
6	2-Carene	12.626	0.48
7	Linalool	13.094	1.24
8	cis-Sabinene hydrate	13.730	0.04
9	2-Bornanone	14.424	0.09
	Terpene:		
1	(1*R*)-2,6,6-Trimethylbicyclo[3.1.1]hept-2-ene	7.077	7.17
	Hidrokarbon teroksigenasi:		
1	1,8-Cineole	10.980	57.91
	Seskuiterpen:		
1	(-)-β-Elemene	21.957	0.06
2	Germacrene D	24.333	0.07
3	β.-Bisabolene	25.054	0.10
4	γ.-Muurolene	25.191	0.08
	Other components:		
1	trans Sabinene hydrate	11.903	0.57
2	2-methyl-5-(1-methyl)bicyclo[3.1.0]hexan-2-ol	12.944	0.12
3	(*E*)-4,8-Dimethylnona-1,3,7-triene	13.649	0.06
4	α,α-Dimethyl-4-cyclohexanemethanol	15.233	0.63
5	4-Methyl-1-(1-methyl)-3-Cyclohexen-1-ol	15.555	0.79
6	α,α-4-Trimethyl-3-cyclohexene-1-methanol	16.041	3.25
7	4-(2-Methoxypropan-2-yl)-1-methylcyclohex-1-en	16.892	0.04
8	1,7-dimethyl-7-(4-methyl)tricyclo[2.2.1.0(2,6)]heptane	22.702	0.06
9	Decahydro-4a-methyl-1-methylene-7-naphthalene	24.469	0.05
10	Cyclohexylmethyl heptadecyl sulfonate	29.716	0.06

lower bulk temperature and the presence of a moist-vapor transport mechanism that mitigates thermal degradation [10][87]. The second sample extracted by MHG contained slightly higher 1,8-cineole (59.65%) than SFME (57.91%), confirming that gentler heating can enhance the retention of thermolabile volatiles [80][88].

Minor constituents such as linalool, γ-terpinene, and β-myrcene add distinctive floral and spicy notes, contributing to the organoleptic and pharmacological complexity of cardamom oil [89]-[91]. β-Myrcene exhibits notable anti-inflammatory and analgesic potential [92], while γ-terpinene acts as a potent antioxidant protecting against lipid peroxidation [93]. Linalool provides calming and anxiolytic effects [94][95]. The combined presence of these compounds gives *A. compactum* oil its unique balance of aroma and bioactivity, making it a valuable multipurpose natural product for the fragrance, flavor, and nutraceutical industries.

Furthermore, SFME and MHG yielded compositional shifts consistent with previous microwave-based extraction studies of *Zingiber officinale* and *Curcuma xanthorrhiza* [62][73]. Such variations likely arise from differences in microwave-energy distribution, moisture dynamics, and dielectric absorption. Environmental conditions, harvest maturity, and local cultivar differences also influence terpenoid biosynthesis [69]. Overall, the higher 1,8-cineole content in MHG supports its potential for energy-efficient, selective extraction of oxygenated volatiles under green-processing principles [11][77]. Hence, GC–MS profiling demonstrated that both SFME and MHG are capable of producing high-quality *A. compactum* essential oil rich in 1,8-cineole. SFME enhanced hydrocarbon fractions through rapid dielectric heating, while MHG improved the preservation of oxygenated terpenes. These complementary effects underline the suitability of integrating microwave-based extraction for tailoring oil composition according to targeted industrial or pharmacological applications.

4. CONCLUSIONS

This study demonstrates that SFME and MHG are highly effective, eco-friendly techniques for extracting essential oil from *A. compactum,* offering substantial advantages over conventional methods like hydrodistillation. Optimization via a BBD revealed that SFME achieved a maximum oil yield of 5.25% at 300 W, a 0.15 g/mL F/D ratio, and 75 min. In contrast, MHG yielded 2.50% under milder conditions (150 W, 0.1 g/mL, 90 min) but demonstrated better preservation of thermolabile compounds. Statistical analysis identified microwave power as the most influential parameter ($p < 0.05$), with MHG exhibiting a stronger interaction between power and the F/D ratio ($p = 0.0430$). GC-MS characterization showed that MHG-produced oil contained 59.65% 1,8-cineole and 1.98% linalool, outperforming SFME, which yielded 57.91% 1,8-cineole and 1.24% linalool. Conversely, SFME enriched hydrocarbon content, particularly 21.53% bicyclo[3.1.1]heptane, indicating distinct selective extraction behavior. Morphological analysis using SEM confirmed 80–90% oil gland rupture and a particle size reduction

Table 8. The compositions of cardamom essential oil using SFME.

No.	Compound name	Mol. Formula	Area (%)	
			SFME	MHG
1	β-Pinene	$C_{10}H_{16}$	0.23	0.30
2	α-Thujene	$C_{10}H_{16}$	8.630	13.94
3	β-Myrcene	$C_{10}H_{16}$	2.90	2.97
4	cis-β-Ocimene	$C_{10}H_{16}$	0.43	0.46
5	γ-Terpinene	$C_{10}H_{16}$	2.06	1.84
6	2-Carene	$C_{10}H_{16}$	0.48	0.42
7	Linalool	$C_{10}H_{18}O$	1.24	1.98
8	cis-Sabinene hydrate	$C_{10}H_{18}O$	0.04	0.00
9	2-Bornanone	$C_{10}H_{16}O$	0.09	0.09
10	α-Pinene	$C_{10}H_{16}$	7.17	6.53
11	1,8-Cineole	$C_{10}H_{18}O$	57.91	59.65
12	β-Elemene	$C_{15}H_{24}$	0.06	0.19
13	Germacrene D	$C_{15}H_{24}$	0.07	0.15
14	β-Bisabolene	$C_{15}H_{24}$	0.10	0.34
15	γ-Muurolene	$C_{15}H_{24}$	0.08	0.25
16	trans-Sabinene hydrate	$C_{10}H_{18}O$	0.57	1.15

to 350 nm post-MHG treatment, corroborating the observed efficiency gains. Both SFME and MHG significantly reduced extraction time to 15–40 min, compared to 3–6 h for conventional methods, representing an 85–95% improvement in time efficiency. In terms of energy consumption, SFME and MHG used only 0.004 and 0.006 kWh/g, respectively (equivalent to 0.4–0.6 kWh/kg), substantially lower than the 8.0 kWh/kg for hydrodistillation and 10.0 kWh/kg for steam distillation, reflecting an energy reduction exceeding 90%. The solvent-free nature of these techniques also eliminated the risk of chemical residues, enhancing product purity. These advancements support multiple SDGs, including SDG 9 (industry, innovation, and infrastructure) through green technology adoption; SDG 12 (responsible consumption and production) by eliminating solvents and reducing waste; and SDG 13 (climate action) via 60–95% energy savings and lower emissions. Practical recommendations include employing pulsed microwave modulation—which reduces hotspot temperatures by 18°C—and vacuum-assisted scale-up at 0.2 bar to enhance the scalability and control of MHG operations. Hence, both SFME and MHG provide sustainable, efficient, and high-yield alternatives for essential oil production from *A. compactum*. SFME is better suited for small-scale, energy-efficient operations, while MHG is superior for industrial-scale applications requiring consistent yield and compound preservation. These technologies align with Indonesia's national agenda for value-added spice processing, further contributing to SDG 8 (decent work and economic growth) and SDG 17 (partnerships for the goals). Future work should focus on integrating real-time temperature monitoring, adaptive microwave control, and pilot-scale validation to ensure reproducibility, enhance oil quality, and accelerate the adoption of circular, low-carbon extraction processes in the essential oil industry.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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DECLARATION OF GENERATIVE AI

During the preparation of this work the author(s) used ChatGPT order to editing manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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