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# Unlocking green efficiency: optimized solvent-free microwave extraction of essential oils from *zingiber officinale*

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**Abstract.** SFME has emerged as a green and efficient technique for essential oil recovery; however, its application to ginger rhizomes and the identification of kinetically operating conditions remain limited. This study investigates the time-dependent extraction behavior and extraction kinetics of ginger essential oil using SFME under varying operating conditions. Microwave power and sample mass were systematically varied to generate yield–time profiles, which were subsequently analyzed using several kinetic models, including first-order, second-order, power law, hyperbolic, Elovich, and Weibull models. The extraction process exhibited a characteristic two-stage behavior, consisting of a rapid initial extraction followed by a slower diffusion-controlled stage. Kinetic analysis revealed that empirical models, particularly the power law and Weibull models, effectively described the non-linear extraction behavior, indicating mixed mass transfer control mechanisms. At a constant microwave power of 450 W, sample mass significantly influenced extraction kinetics, with intermediate solid loading providing a balanced extraction rate and favorable characteristic extraction time. Based on kinetic efficiency and extraction stability rather than final yield alone, the optimal operating condition was identified at 450 W with a sample mass of 200 g. This kinetic-based evaluation provides mechanistic insight into SFME of ginger and offers a rational efficient operating conditions for green extraction.

## 1 Introduction

Essential oils (EOs) are volatile, aromatic substances extracted from various parts of plants, including leaves, seeds, rhizomes, and flowers. They are widely valued for their multifaceted biological activities such as antimicrobial, anti-inflammatory, antioxidant, and anticancer effects, making them important ingredients in the pharmaceutical, cosmetic, and food industries [1]. In recent years, global consumer interest in plant-based natural products has driven significant research into developing more efficient, sustainable, and scalable extraction technologies for essential oils.

Among the many plants exploited for their essential oils, ginger (*Zingiber officinale*) is particularly important due to its rich chemical composition and established health benefits.

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Ginger rhizomes contain a wide variety of bioactive compounds, notably terpenes and phenolics, which contribute to their pharmacological and sensory properties [2]. The essential oil of ginger is reported to exhibit strong antioxidant and antimicrobial potential, which supports its broad application in traditional medicine, aromatherapy, and nutraceutical formulations. Within this species, the *Zingiber officinale* stands out due to its larger rhizome size, pale-yellow color, and high essential oil content [3]. These features make it an attractive varietal for industrial processing; however, there is a noticeable gap in research regarding the systematic optimization of its oil extraction process.

Traditionally, essential oils are extracted using hydrodistillation, steam distillation, or solvent extraction methods. While these techniques are widely accepted, they are associated with various drawbacks such as high energy consumption, long extraction times, and risk of thermal degradation of sensitive compounds [4]. In addition, the use of organic solvents poses environmental and health concerns due to solvent residue in the final product. These limitations have stimulated interest in modern extraction technologies that offer greener, faster, and more selective processes.

Solvent-Free Microwave Extraction (SFME) is one such emerging green technique that has gained attention for its efficiency and sustainability. SFME employs microwave dielectric heating to rapidly and selectively heat water within plant cells, generating internal pressure that causes cell rupture and the subsequent release of essential oils [5].The major advantages of SFME include solvent elimination, reduced extraction time, lower energy use, and better retention of thermolabile compounds compared to conventional techniques [6]. Furthermore, SFME can be performed at atmospheric pressure, and its scalability makes it suitable for both laboratory and industrial settings.

While SFME has been successfully applied to various aromatic plants such as lemongrass, peppermint, and cananga, its application to *Zingiber officinale* remains limited. Previous studies have demonstrated the feasibility of microwave-assisted extraction on ginger rhizomes [10]; however, most investigations emphasize extraction performance under fixed operating conditions or focus primarily on kinetic modeling without explicitly identifying optimum extraction conditions. As a result, the time-dependent extraction behavior and kinetically favorable operating conditions for SFME of ginger remain insufficiently explored.

The novelty of this study lies in the kinetic evaluation of solvent-free microwave extraction of ginger rhizomes to identify optimum operating conditions based on yield maximization and extraction rate behavior. Rather than employing multivariate numerical optimization, the optimum condition in this work is defined as the operating condition that achieves the highest extraction yield with efficient kinetic performance, thereby avoiding unnecessary energy input and excessive extraction time.

Microwave power and extraction time were systematically varied to generate yield–time profiles, which were subsequently analyzed using kinetic models to determine extraction rate constants and characteristic extraction stages. Microwave power governs the internal heating rate and cell rupture intensity, directly influencing the initial extraction rate, while extraction time controls the approach toward equilibrium yield [8]. Through kinetic interpretation, the optimum SFME condition was identified as the condition that provides the maximum oil yield while maintaining favorable extraction kinetics.

This kinetic-based determination of optimum operating conditions provides a rational framework for evaluating SFME performance for ginger extraction and offers fundamental insight for future process optimization and scale-up studies [9].

Accordingly, this study aims to investigate the effects of microwave power, extraction time, and sample mass on the essential oil yield from *Zingiber officinale* using the solvent-free microwave extraction (SFME) method. In addition, the extraction kinetics of SFME are analyzed through mathematical modeling to describe the time-dependent extraction behavior and to determine kinetically favorable operating conditions based on yield maximization.

Furthermore, this study seeks to identify and experimentally validate the optimum SFME operating condition that produces the highest essential oil yield while maintaining efficient extraction kinetics. The study aims to address the current knowledge gap in the application of SFME to ginger and provide a mechanistic foundation for selecting efficient operating conditions. The outcomes are expected to support future process optimization and scale-up studies, as well as contribute to the development of sustainable and high-efficiency green extraction technologies for essential oil–rich medicinal plants.

# 2 Research Methods

## 2.1 Material and Equipment

Fresh rhizomes of *Zingiber officinale* were sourced from a local agricultural market in Surabaya, Indonesia. The rhizomes were selected based on visual uniformity, maturity (7–9 months post-planting), and the absence of physical damage or microbial spoilage. Upon arrival, the samples were washed thoroughly with distilled water to remove dirt and debris, and then sliced into thin uniform sections approximately 2–3 mm thick. No drying or pre-treatment was applied to maintain the native moisture level for microwave-assisted extraction.

The extraction was performed using a domestic microwave oven (Electrolux EMM20K22BA, 2450 MHz, maximum power 800 W), modified and fitted with a 1000 mL double-necked round-bottom flask connected to a Clevenger-type apparatus for essential oil collection (Figure 1). The condenser was maintained at low temperature using a refrigerated water circulator to ensure complete condensation of volatiles. The sample mass was weighed using a digital analytical balance (±0.01 g precision), and a stopwatch was used to monitor extraction time. The essential oils were collected in glass vials, sealed tightly, and stored in the dark at 4 °C until further quantification.

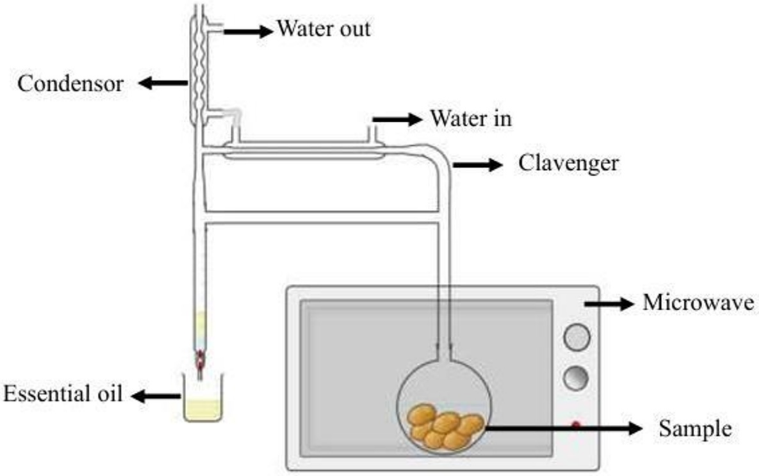

**Fig. 1.** SFME experimental set-up

## 2.2 Solvent – Free Microwave Extraction (SFME) Procedure

The SFME method was conducted without the addition of any solvent or water. A predetermined amount of fresh ginger sample (100–300 g) was placed in the round-bottom flask. The system was irradiated with microwave energy at designated power levels (300–600 W) for varying durations (60–180 minutes), according to the experimental design matrix. During extraction, the water content naturally present in the plant matrix was vaporized by microwave heating, generating internal pressure that disrupted plant cell walls and released volatile compounds (Figure 2).

The released vapors were passed through the condenser, where they condensed into a two-phase liquid consisting of water and essential oil. The oil layer was manually separated using a pipette or separatory funnel, measured gravimetrically, and expressed as yield (% w/w) relative to the initial mass of fresh rhizome. Each experimental condition was performed in duplicate to ensure reproducibility.

**Fig. 2.** Solvent Free Microwave Extraction Scheme

## 2.3 Kinetic Modelling

The extraction kinetics were evaluated using various mathematical models, including pseudo-first-order, pseudo-second-order, power law, hyperbolic, and Elovich models. These models were applied to the experimental data to estimate rate constants and identify the underlying extraction mechanisms. In addition, Peleg's model—a type of hyperbolic model—was utilized to characterize the mass transfer behavior during the extraction process. The kinetic models assessed in this study are presented in Table 1. Nonlinear regression analysis was employed to estimate the parameters for each model. The most appropriate model was selected based on goodness-of-fit indicators such as the coefficient of determination ($R^2$) and root mean square error (RMSE) [13].

**Table 1.** Kinetics model of extraction

| Kinetic Model | Equation model | Refs |
|---|---|---|
| 1. 1st-Order | $\frac{C_t}{C_S} = (1 - e^{-kt})$ | 1 |
| 2. 2nd-Order | $\frac{C_t}{C_S} = \frac{C_S k_2 t}{1 + C_S k_2 t}$ | 2 |

| | | | |
|---|---|---|---|
| 3. | Power Law | $\frac{C_t}{C_S} = B.t^n$ | 3 |
| 4. | Hyperbolic | $\frac{C_t}{C_S} = \frac{k_1 t}{1 + k_2 t}$ | 4 |
| 5. | Elovich’s | $\frac{C_t}{C_S} = E_0 + E_1 \, x \, lnt$ | 5 |

## 3 Result and Discussion

### 3.1 Time – Dependent Extraction Behavior of SFME

The time-dependent extraction behavior of essential oil from *Zingiber officinale* using solvent-free microwave extraction (SFME) was evaluated based on yield–time data obtained under various operating conditions. The experimental results reveal a non-linear extraction profile, indicating that the extraction rate changes progressively with time and operating parameters. Variations in microwave power and sample mass significantly influence the shape of the extraction curves and the time required to approach equilibrium, suggesting the involvement of multiple mass transfer phenomena during the SFME process [8].

Overall, the SFME process exhibited a characteristic two-stage extraction behavior, consisting of an initial fast extraction stage followed by a slower diffusion-controlled stage. Under all investigated conditions, a rapid increase in yield was observed during the early extraction period, indicating efficient microwave-induced cell rupture and fast release of readily accessible essential oil [9]. This stage was particularly pronounced under moderate microwave power, where internal heating was sufficient to enhance oil liberation without causing excessive thermal degradation.

Among the investigated conditions, the highest essential oil yield was obtained at a microwave power of 450 W with a sample mass of 200 g, reaching approximately 1.5–1.6% after 150–180 minutes of extraction. Under this condition, the extraction curve exhibited a steep initial slope followed by a gradual approach toward equilibrium, reflecting a favorable balance between extraction rate and yield. Lower microwave power (300 W) resulted in slower yield development and lower final yield, whereas higher power (600 W) accelerated the initial extraction but tended to shorten the fast extraction stage, likely due to rapid depletion of easily accessible oil and potential thermal effects.

Sample mass also influenced the extraction behavior by affecting microwave energy distribution and mass transfer resistance. A moderate sample mass (200 g) provided more uniform volumetric heating and efficient vapor diffusion, whereas excessive biomass loading delayed the approach to equilibrium. These observations indicate that both microwave power and sample mass govern the relative contributions of the fast and slow extraction stages.

The observed yield–time behavior confirms that SFME of ginger is governed by a combination of microwave-induced cell rupture and subsequent diffusion-driven mass transfer. The condition yielding the highest extraction efficiency was therefore selected as the kinetically favorable operating condition, which was subsequently analyzed using kinetic models to quantitatively describe the extraction process, as discussed in the following sections.

### 3.2 Kinetics Models and Data Fittings

Multiple kinetic models were employed in this study to comprehensively describe the complex extraction behavior of SFME rather than to identify a single best-fitting equation. Each model represents different assumptions regarding mass transfer mechanisms, including concentration-driven kinetics, heterogeneous surface effects, and diffusion-controlled transport. The use of multiple models enables a mechanistic interpretation of the extraction process by comparing parameter trends and model performance under varying operating conditions. Therefore, the selection of kinetic models in this study was intended to elucidate extraction mechanisms and rate-controlling steps, rather than to achieve purely statistical curve fitting.

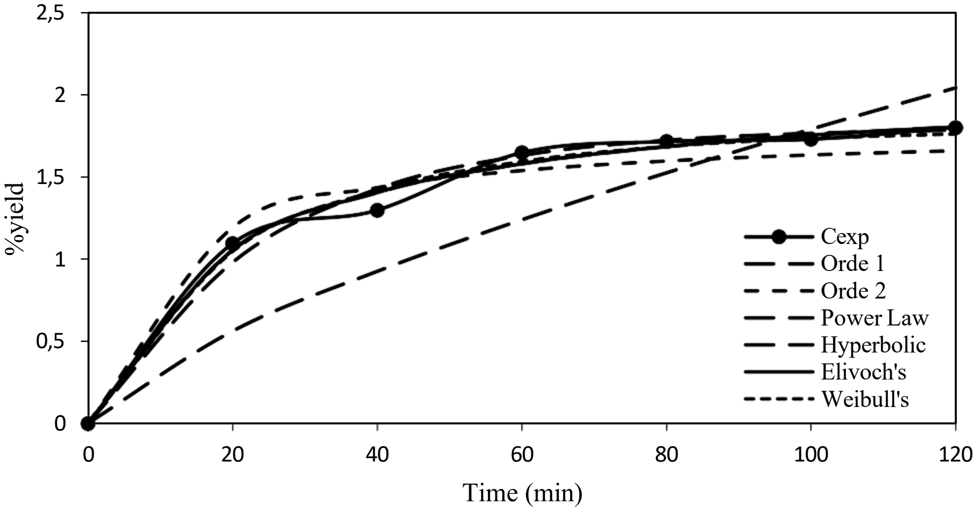

**Fig. 3.** Comparison of Experimental Data and Model Calculations for SFME (450W, 100gram)

**Table 2.** Kinetic Model of SFME (450W, 1cm, 100gram)

| Order 1 | | Order 2 | | Power law | | Hyperbolic | | Elovich's | | Weibull's | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| k | 0.017 | k | 0.054 | B<br>n | 0.065<br>0.721 | $C^1$<br>$C^2$ | 0.106<br>0.050 | Eo<br>$E_1$ | 0.106<br>0.050 | α<br>β | 23.64<br>0.827 |
| $R^2$ | 0.921 | $R^2$ | 0.620 | $R^2$ | 0.971 | $R^2$ | 0.718 | $R^2$ | 0.718 | $R^2$ | 0.698 |
| SSE | 0.068 | SSE | 0.128 | SSE | 0.152 | SSE | 0.237 | SSE | 0.237 | SSE | 0.173 |

Figure 3 and Table 2 present the time-dependent extraction behavior of SFME at a microwave power of 450 W using 100 g of raw material, together with the corresponding predictions of several kinetic models. The experimental data exhibit a pronounced non-linear increase in extraction yield with time, particularly during the early stage of the process. A rapid rise in yield is observed within the first 20–30 minutes, indicating that a significant portion of the extractable compounds is readily released at the beginning of extraction. This behavior can be attributed to the effect of microwave heating, which induces internal heating and localized pressure gradients within the plant matrix, facilitating structural disruption and enhancing the initial mass transfer of solutes into the extraction medium.

As extraction time increases, the rate of yield enhancement gradually declines, and the extraction curve approaches an asymptotic trend. This change reflects a transition from a fast initial extraction stage to a slower regime dominated by internal diffusion and matrix resistance. At this stage, the remaining compounds are increasingly confined within less accessible regions of the solid matrix, resulting in reduced mass transfer rates despite continued energy input. The progressive flattening of the experimental curve suggests that the extraction system is approaching a quasi-equilibrium condition, where further solute release becomes increasingly limited.

Comparison between the experimental data and the model-generated curves indicates that the extraction process cannot be adequately described by a single linear kinetic expression. While the first-order model reasonably captures the overall trend, noticeable deviations are observed, particularly at short extraction times, whereas the second-order model shows poorer agreement over the full extraction period. Empirical models such as the power law, Weibull, hyperbolic, and Elovich equations better accommodate the non-linear nature of the extraction process, although differences in fitting accuracy remain evident. These observations confirm the presence of multi-stage extraction kinetics and provide a clear rationale for the application of kinetic modeling to further elucidate the underlying extraction mechanism in subsequent sections [1, 10].

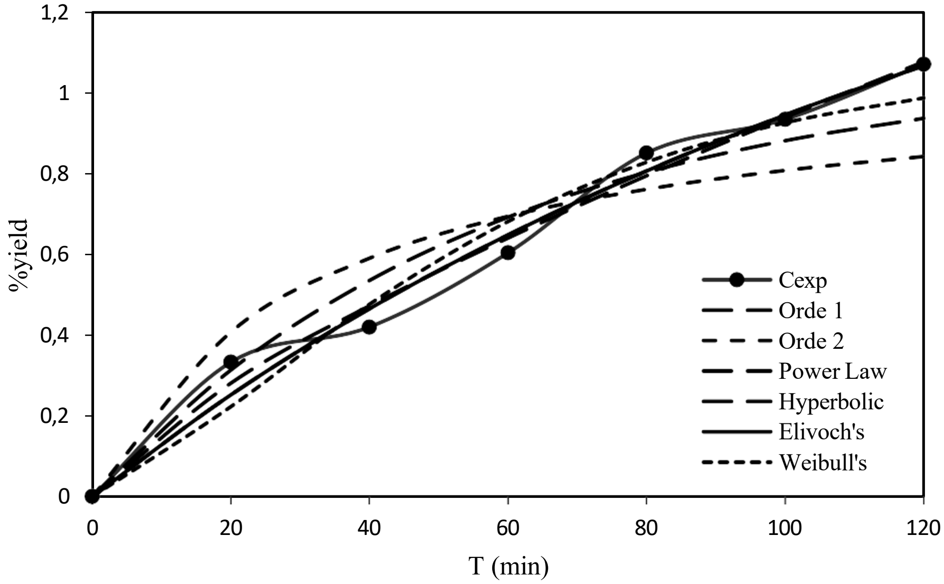

**Fig. 4.** Comparison of Experimental Data and Model Calculations for SFME (450W, 200gram)

**Table 3.** Kinetic Model of SFME (450W, 200gram)

| Order 1 | | Order 2 | | Power law | | Hyperbolic | | Elovich’s | | Weibull’s | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| k | 0.018 | k | 0.029 | B<br>n | 0.030<br>0.749 | $C^1$<br>$C^2$ | 0.014<br>0.004 | Eo<br>$E_l$ | 0.014<br>0.004 | α<br>β | 312.3<br>1.335 |
| $R^2$ | 0.939 | $R^2$ | 0.851 | $R^2$ | 0.959 | $R^2$ | 0.969 | $R^2$ | 0.969 | $R^2$ | 0.977 |
| SSE | 0.105 | SSE | 0.059 | SSE | 0.032 | SSE | 0.028 | SSE | 0.028 | SSE | 0.026 |

Figure 4 and Table 3 depict the time-dependent extraction behavior of SFME performed at a microwave power of 450 W with a solid loading of 200 g, together with the corresponding predictions of several kinetic models. Similar to the lower solid mass condition, the experimental extraction yield increases progressively with time, although the overall extraction rate is noticeably slower. During the initial extraction period, the yield rises gradually, indicating that the availability of readily extractable compounds is more limited when a higher solid mass is employed. The increased solid loading likely leads to a denser matrix structure and reduced effective exposure of the solid surface, which moderates the early-stage mass transfer despite the same microwave power input.

As extraction proceeds, the yield continues to increase in a nearly linear fashion before gradually approaching an asymptotic trend at longer extraction times. This behavior suggests that the extraction process is increasingly governed by internal diffusion and matrix resistance, which become more pronounced at higher solid mass. The delayed approach to equilibrium observed in Figure 4 reflects the greater diffusion path length and reduced solvent accessibility within the bulk solid matrix. Consequently, the extraction process exhibits a more prolonged kinetic profile compared to the 100 g condition, highlighting the influence of solid loading on the temporal evolution of extraction yield.

The comparison between experimental data and kinetic model predictions shows improved overall agreement for most models under this condition. The first-order and second-order models capture the general extraction trend with relatively high coefficients of determination, although minor deviations are still observed at intermediate extraction times. Empirical models, particularly the power law, hyperbolic, Elovich, and Weibull equations, demonstrate closer conformity with the experimental data over the full time range, indicating their greater flexibility in representing non-linear extraction kinetics at higher solid mass. These results further confirm that SFME under the studied conditions follows a multi-stage extraction mechanism and provide a consistent phenomenological basis for subsequent kinetic parameter analysis.

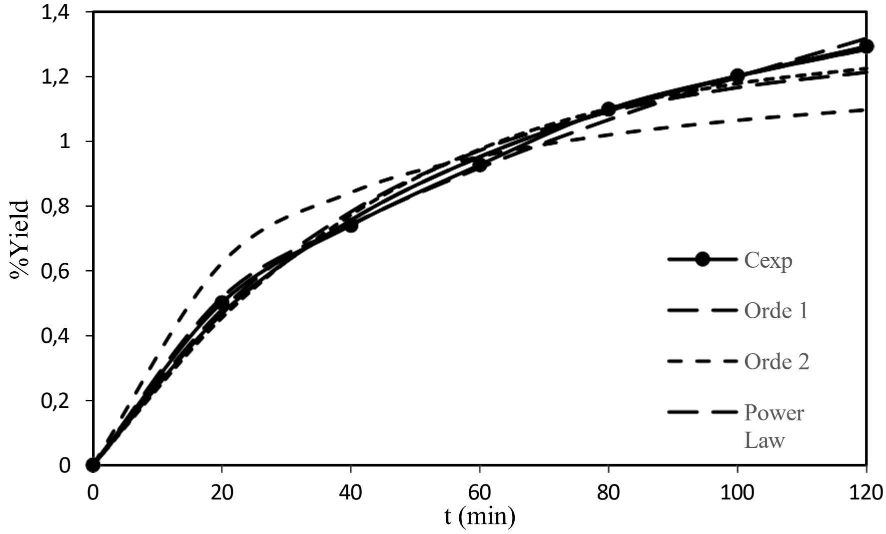

**Fig. 5.** Comparison of Experimental Data and Model Calculations for SFME (450W, 300gram)

**Table 4.** Kinetic Model of SFME (450W, 300gram)

| Order 1 | | Order 2 | | Power law | | Hyperbolic | | Elovich's | | Weibull's | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| k | 0.018 | k | 0.036 | B<br>n | 0.108<br>0.522 | $C^1$<br>$C^2$ | 0.031<br>0.015 | Eo<br>$E_1$ | 0.031<br>0.015 | α<br>β | 43.72<br>1.070 |
| $R^2$ | 0.944 | $R^2$ | 0.927 | $R^2$ | 0.942 | $R^2$ | 0.937 | $R^2$ | 0.937 | $R^2$ | 0.913 |
| SSE | 0.018 | SSE | 0.029 | SSE | 0.238 | SSE | 0.239 | SSE | 0.239 | SSE | 0.026 |

Figure 5 and Table 4 illustrate the time-dependent extraction behavior of SFME at a microwave power of 450 W with a solid mass of 300 g, along with the corresponding predictions of several kinetic models. The experimental extraction profile shows a gradual and continuous increase in extracted compound mass with time, characterized by a less pronounced initial rise compared to lower solid loadings. This trend indicates that increasing the solid mass further limits the availability of readily extractable compounds at the early stage of extraction. The denser packing of the solid matrix and the increased diffusion path length likely hinder rapid solute release, resulting in a more moderated initial extraction rate under otherwise identical operating conditions.

As the extraction progresses, the yield continues to increase steadily before approaching a plateau at extended extraction times. The absence of a sharp transition between extraction stages suggests that diffusion resistance dominates the mass transfer process throughout most of the extraction period. At higher solid mass, the extraction system requires a longer time to approach equilibrium, reflecting the cumulative effect of matrix compaction and reduced solvent accessibility. The gradual curvature of the experimental data confirms that the extraction process becomes increasingly controlled by internal mass transfer limitations as the solid loading increases.

The comparison between experimental data and model calculations reveals that most kinetic models provide a reasonable representation of the extraction behavior under this condition. The first-order and second-order models show good agreement with the experimental data, as reflected by relatively high coefficients of determination, indicating that concentration-dependent kinetics become more dominant at higher solid mass. Empirical models, including the hyperbolic, Elovich, and Weibull equations, also capture the overall extraction trend, although deviations are still observed in the later extraction stage. These results reinforce the conclusion that SFME at high solid loading follows a multi-stage kinetic process, with diffusion-controlled mechanisms playing a central role, thereby providing a consistent phenomenological basis for subsequent kinetic parameter interpretation.

### 3.3 Interpretation Kinetics Parameters

The kinetic parameters obtained from the fitting of various models provide deeper insight into the underlying extraction mechanism of SFME at a constant microwave power of 450 W under different solid loadings. The first-order rate constant ($k_1$) exhibits relatively similar values across all solid masses, ranging from 0.017 to 0.018 min$^{-1}$. This limited variation suggests that the intrinsic extraction rate driven by concentration gradients is primarily governed by the applied microwave power rather than by solid loading. However, despite comparable $k_1$ values, the overall extraction profiles differ substantially, indicating that first-order kinetics alone are insufficient to fully describe the extraction process, particularly as solid mass increases and internal diffusion resistance becomes more pronounced.

In contrast, the second-order rate constant ($k_2$) shows a noticeable dependence on solid loading, with values increasing from 0.029 to 0.054 as the mass decreases. This trend reflects the greater contribution of solute–matrix interactions and concentration-dependent limitations at higher solid masses. The improved fitting performance of the second-order model at 300 g, compared to lower masses, suggests that extraction at high solid loading increasingly follows concentration-controlled behavior, where the rate of solute release becomes sensitive to the remaining solute concentration within the matrix. Nevertheless, the second-order model still fails to adequately capture the early extraction stage, highlighting the presence of additional transport mechanisms beyond simple reaction-order assumptions.

The power law model provides important mechanistic information through its parameters B and n. The exponent n ranges between 0.52 and 0.75 across the investigated solid masses, consistently remaining below unity. This fractional exponent indicates non-Fickian mass transfer behavior, confirming that the extraction process is governed by a combination of rapid initial release and slower diffusion-controlled transport. Notably, the decrease in n with increasing solid mass suggests a shift toward diffusion-dominated kinetics, as the extraction pathway becomes increasingly constrained by longer diffusion distances and reduced solvent accessibility within the bulk matrix. The flexibility of the power law model in capturing this mixed-control behavior explains its consistently high coefficients of determination across all conditions.

The hyperbolic and Elovich models further support the presence of heterogeneous extraction kinetics. The parameters $C_1$ and $E_0$, which represent the initial extraction rate, decrease systematically with increasing solid mass, indicating a reduction in readily accessible solute fractions at higher loadings. Simultaneously, the corresponding decay parameters ($C_2$ and $E_1$) reflect a rapid decline in extraction rate as extraction progresses, consistent with progressive depletion of easily extractable compounds. The comparable fitting performance of these two models suggests that the extraction surface becomes increasingly heterogeneous over time, with a diminishing number of active sites contributing to solute release.

The Weibull model offers additional insight through its scale ($\alpha$) and shape ($\beta$) parameters. The scale parameter $\alpha$ increases substantially with solid mass, indicating that a longer characteristic time is required to reach a given fraction of total extraction as the matrix becomes more compact. Meanwhile, the shape parameter $\beta$ remains close to or slightly above unity, reflecting a decelerating extraction rate over time. This behavior is characteristic of systems where the extraction rate decreases continuously due to increasing internal resistance, further confirming the dominance of diffusion-controlled mechanisms at higher solid loading.

Taken together, the interpretation of kinetic parameters across different solid masses demonstrates that SFME at constant microwave power is governed by a multi-stage extraction mechanism. While the applied power establishes the driving force for extraction, solid loading strongly influences the balance between rapid initial release and diffusion-limited transport. The combined analysis of empirical and semi-empirical models reveals that no single kinetic expression can fully describe the extraction behavior across all conditions; instead, the observed kinetics result from the interplay between matrix structure, solute accessibility, and time-dependent mass transfer resistance. These findings provide a robust mechanistic foundation for identifying optimal extraction conditions based on kinetic behavior rather than solely on final extraction yield. The observed two-stage extraction behavior and non-Fickian diffusion characteristics are consistent with previous reports on microwave-based extraction of ginger and other essential oil–bearing plants. Similar values of the diffusion exponent ($n < 1$) have been reported for microwave-assisted extraction of ginger and aromatic herbs, indicating mixed control between rapid solute release and internal diffusion. These similarities suggest that the kinetic behavior observed in this study aligns well with established extraction mechanisms reported in the literature.

### 3.4 Determination of Optimal Extraction Condition Based on Kinetic Behavior

The determination of the optimal extraction condition was carried out by integrating the kinetic behavior and parameter interpretation obtained from the previous sections, rather than relying solely on final extraction yield. At a constant microwave power of 450 W, variations in solid loading significantly influenced the temporal evolution of extraction and the dominant mass transfer mechanisms. Lower solid mass (100 g) exhibited a rapid initial extraction stage, characterized by higher apparent extraction rates and earlier attainment of a quasi-equilibrium state. This behavior indicates a more efficient utilization of the applied microwave energy, resulting in enhanced solute accessibility and reduced internal diffusion resistance.

At intermediate solid loading (200 g), the extraction process displayed a more balanced kinetic profile. Although the initial extraction rate was lower than that observed at 100 g, the system maintained a relatively sustained extraction rate over a longer time period. The kinetic parameters derived from empirical models showed improved fitting performance under this condition, suggesting a more stable and predictable extraction behavior. This indicates that the extraction process at 200 g benefits from a compromise between solute availability and diffusion resistance, allowing effective mass transfer without excessive limitation from matrix compaction.

In contrast, the highest solid loading (300 g) resulted in a noticeably prolonged extraction process, with diffusion-controlled mechanisms dominating throughout most of the extraction period. Despite achieving a comparable final extraction yield at extended times, the kinetic parameters revealed increased characteristic extraction times and reduced initial extraction rates. From a kinetic perspective, this condition requires longer processing times to approach equilibrium, which may be unfavorable when extraction efficiency and energy utilization are considered. Based on the combined evaluation of extraction rate, kinetic stability, and characteristic extraction time, the optimal condition at 450 W is identified within the lower to intermediate solid loading range. While 100 g provides the fastest extraction kinetics, 200 g offers a more controlled and reproducible extraction profile with favorable kinetic parameters and reduced sensitivity to diffusion limitations. Therefore, the selection of the optimal condition should prioritize kinetic efficiency and process practicality rather than maximum yield alone, reinforcing the importance of kinetic-based evaluation for rational process design.

From a practical perspective, the kinetically favorable condition identified in this study implies reduced extraction time and more efficient energy utilization, which are critical parameters for industrial-scale SFME. The balanced extraction kinetics observed at intermediate solid loading suggest improved process controllability and scalability, supporting the potential application of SFME as an energy-efficient and solvent-free alternative for essential oil production.

## 3.5 GC–MS Results of Ginger Essential Oil

**Table 5.** Major volatile compounds of *Zingiber officinale* essential oil

| No. | Compound | R.Time | Similarity | % Area | % Component |
|---|---|---|---|---|---|
| 1 | Citral | 15.400 | 89 | 1.00 | 3.42 |
| 2 | Neral | 15.505 | 96 | 0.67 | 2.29 |
| 3 | Geraniol | 16.237 | 96 | 0.16 | 0.51 |
| 4 | α-Terpineol | 14.159 | 95 | 0.09 | 0.24 |
| 5 | Linalool | 11.305 | 97 | 0.06 | 0.21 |
| 6 | Citronellol | 15.463 | 94 | 0.05 | 0.17 |
| 7 | Eucalyptol | 9.779 | 93 | 0.03 | 0.10 |
| 8 | Camphor | 12.572 | 88 | 0.02 | 0.07 |

Gas Chromatography–Mass Spectrometry (GC–MS) analysis revealed that the ginger essential oil obtained by solvent-free microwave extraction (SFME) consisted predominantly of oxygenated monoterpenes with varying relative abundances, as summarized in Table 5. Among the identified compounds, citral was the most abundant constituent, accounting for 3.42% of the total peak area, followed by neral (2.29%), both of which are key aldehydic monoterpenes responsible for the characteristic lemon-like aroma of ginger essential oil. The presence of citral and neral indicates that the SFME process was effective in recovering thermally sensitive volatile compounds without significant degradation.

In addition to aldehydic monoterpenes, several oxygenated monoterpene alcohols were detected at lower concentrations, including geraniol (0.51%), α-terpineol (0.24%), linalool (0.21%), and citronellol (0.17%). These compounds are widely recognized for their contributions to floral, sweet, and fresh aroma notes, as well as for their reported biological activities such as antimicrobial and antioxidant effects. Although present in relatively minor proportions, these monoterpenes play a crucial role in defining the sensory complexity and functional properties of ginger essential oil.

Furthermore, other oxygenated monoterpenes such as eucalyptol (1,8-cineole, 0.10%) and camphor (0.07%) were also identified. These compounds are commonly associated with camphoraceous and cooling aroma characteristics and are frequently reported as minor constituents in ginger essential oil. Their detection suggests that the applied SFME conditions were sufficiently mild to preserve volatile and thermally sensitive compounds that are often susceptible to loss during prolonged conventional heating.

Overall, the GC–MS profile demonstrates that ginger essential oil extracted via SFME exhibits a chemically diverse composition dominated by oxygenated monoterpenes, particularly citral and its isomers. This compositional profile highlights the capability of the SFME technique to selectively recover characteristic ginger volatiles while maintaining their chemical integrity, which is essential for both aroma quality and potential bioactivity.

## 4. Conclusions

The solvent-free microwave extraction of essential oil from *Zingiber officinale* exhibited a clear multi-stage kinetic behavior, characterized by a rapid initial extraction followed by a diffusion-controlled regime. Kinetic modeling demonstrated that empirical models, particularly the power law and Weibull models, effectively described the non-linear extraction behavior and reflected mixed mass transfer control mechanisms. At a constant microwave power of 450 W, solid loading significantly influenced extraction kinetics, with an intermediate sample mass of 200 g providing the most favorable balance between extraction rate, stability, and characteristic extraction time. These findings confirm that kinetic-based evaluation offers a rational basis for defining optimal SFME operating conditions and supports the development of efficient and sustainable green extraction processes.

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