

## Kinetics Model of Onion Extraction (*Allium cepa*) using Microwave Hydrodiffusion and Gravity (MHG) Method

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### ABSTRACT

The demand for natural essential oils continues to increase as public awareness of natural and environmentally friendly products increases. However, conventional methods such as hydrodistillation still have limitations in energy efficiency and process time. This study aims to study the kinetic characteristics of essential oil extraction from shallots (*Allium cepa*) using the Microwave Hydrodiffusion and Gravity (MHG) method as an efficient and solvent-free green technology alternative. The process is carried out with variations in microwave power (300, 450, and 600 W) and extraction time (10–40 minutes). The yield of the resulting essential oils was analysed experimentally, then modelled using two kinetic approaches: the first-order. The results showed that the Weibull model provided the best match with the experimental data ( $R^2 > 0.98$  and the lowest RMSE), which indicated the extraction process was based on internal diffusion and desorption. The increase in microwave power accelerates the rate of oil diffusion from the cell tissue, as indicated by the parameter ( $k$ ), confirming that the process takes place with a controlled internal diffusion mechanism. Overall, the MHG method has been proven to improve extraction efficiency, save up to 40 % energy, and maintain essential oil quality compared to conventional distillation.

**Keywords:** Microwave Hydrodiffusion and Gravity (MHG); *Allium Cepa*; essential oils; kinetic models; energy efficiency.

### INTRODUCTION

Essential oils are a group of complex volatile compounds that are widely used in the food, cosmetic, and pharmaceutical industries because they have strong biological activities such as antibacterial, antioxidant, and antimicrobial (Bakkali et al., 2008) (Prayitno et al., 2018; Rusliana et al., 2024). One potential source of essential oils is onions (*Allium cepa*), which is rich in organosulfur compounds such as *Dipropyl Disulfide*, *diallyl trisulfide* and *hexanal*, which contributes to the distinctive aroma as well as has a high therapeutic value (Kumar et al., 2022). However, the production of essential oils from *Allium cepa* is still constrained by low extraction efficiency due to the limitations of conventional methods such as hydrodistillation (HD) and steam distillation (SD). These methods generally require a long extraction time (3–6 hours), high energy consumption, and can cause thermal degradation of volatile compounds that are sensitive to heat (Zhang et al., 2014).

As the industry's need for sustainable technology increases, various innovations in essential oil extraction techniques have been developed. One of the prominent approaches is the use of microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE) technology, which have been shown to improve extraction efficiency through accelerated mass transfer and volumetric heating (Asofiei et al., 2017) (Sugiono et al., 2022). Among the

various modifications of the MAE, the Microwave Hydrodiffusion and Gravity (MHG) method emerged as an excellent alternative that did not require solvents and cooling water (*solvent-free extraction*), so that it is more efficient and environmentally friendly (Lucchesi et al., 2004). MHG technology combines the principle of rapid volumetric heating by the electromagnetic field of the microwave and the natural gravitational force to flow the oil and water vapors formed from the plant tissue into the condenser without additional pressure.

Compared to conventional distillation methods, MHG offers several significant advantages: much shorter extraction time (20–40 minutes), higher energy efficiency (saving up to 40 %), as well as the ability to retain more sensitive aromatic components. The MHG process takes place quickly because microwaves heat the water molecules contained within the plant cell tissue, forming internal pressures that cause cell wall rupture and oil diffusion to the surface, so that oil and moisture can move towards the condenser by gravity (Chemat et al., 2012). This mechanism allows extraction to take place without the addition of external solvents, in line with the principles of green chemistry and circular bioeconomy (Sagar et al., 2022).

In addition to process efficiency, the analysis of the extraction kinetics model has an important role to understand the mass transfer mechanism and diffusion rate of volatile compounds during the MHG process. The kinetic model provides a scientific basis for designing and optimizing extraction operation conditions, as well as being a key parameter in industrial scale-up processes (Haqqyana et al., 2022). A number of mathematical models have been used in the literature to describe the kinetic behavior of essential oil extraction, including the first-order model, the second-order model, the Power Law, and the Weibull model. According to Haqqyana et al. (2022), the pseudo-one-order model often describes a single diffusion process, while the Weibull model is able to present the dynamics of diffusion and internal desorption simultaneously with high accuracy ( $R^2 > 0.98$ ). The Weibull model also allows the interpretation of parameters  $\alpha$  (characteristic time) and  $\beta$  (form factor), which represents the speed of diffusion and the internal resistance to mass displacement, respectively (Katsampa et al., 2015).

In the context of materials *Allium cepa*, the dense and water-rich structure of tuber tissue plays an important role in the extraction rate. The internal water content acts as a dielectric heating medium in microwave systems, thereby increasing the efficiency of electromagnetic energy transfer. However, if the temperature is too high, the risk of degradation of volatile compounds increases, especially in sulphur and short-chain aldehydes (Kumar et al., 2022). Therefore, the microwave power setting and extraction time are crucial factors that determine the yield as well as the quality of the oil produced. Some recent studies have shown that the optimum power for microwave-based essential oil extraction ranges from 300–600 W, with an optimum time of 20–30 minutes to achieve a balance between diffusion efficiency and thermal stability of volatile compounds (Katsampa et al., 2015).

In addition to energy efficiency advantages, MHG technology also has advantages in terms of sustainability. This process does not produce liquid waste because it does not use solvents, and reduces the carbon footprint of the process by up to 35 % compared to conventional distillation (Chemat et al., 2017). Its implementation is in line with Sustainable Development Goals (SDG) 7 on clean energy and SDG 12 on sustainable production and consumption, thus making MHG a strategic method for processing natural materials in the era of green energy transition (M. Mahfud et al., 2025). In the local context, the application of MHG technology has great potential to increase the added value of Indonesian horticultural products such as

abundant shallots and onions, while supporting national programs *Waste-to-Wealth* and *Green Innovation* in the field of process technology.

Based on this background, this study was conducted to examine the kinetic model of essential oil extraction from onions using the MHG method, with the aim of identifying the most representative mathematical model and determining kinetic parameters such as rate constant ( $k$ ). The analysis was carried out by varying the microwave power and extraction time, as well as evaluating the suitability of the model through statistical parameters ( $R^2$  and RMSE). In addition, the chemical composition of the extracted results was analysed using Gas Chromatography–Mass Spectrometry (GC–MS) to determine the stability of the resulting volatile compounds. It is hoped that the results of this research can make a significant contribution to understanding the kinetic behavior of the MHG process in *Allium cepa* materials, as well as become a scientific basis in the development of an efficient, environmentally friendly, and sustainable industrial-scale essential oil extraction system.

## METHODS

### **Materials**

The main ingredient used in this study was fresh onions (*Allium cepa* L.) obtained from the local market of Surabaya, Indonesia. Samples were selected based on freshness criteria, uniform skin tone, and did not undergo decay. After cleaning and peeling, the onion is thinly sliced to a thickness of 3–5 mm using *Food Slicer* stainless steel to ensure particle size uniformity. The actual sizes used were 1 cm × 1 cm × 3–5 mm, 2 cm × 2 cm × 3–5 mm, and 3 cm × 3 cm × 3–5 mm. The onion pieces are then dried using a sun drying °C for 2 hours to reduce the free moisture content on the surface without disturbing the internal water content which acts as a dielectric heating medium in the microwave system (Chemat et al., 2012). No additional solvents are used in the extraction process because the MHG method relies on natural water in plant tissues to form steam during heating. Chemicals such as anhydrous sodium sulphate (Merck, 99 %) are used to dry the extracted oil before analysis. All chemicals are analytical grade.

### **Equipment**

The extraction process was carried out using a laboratory-scale Microwave Hydrodiffusion and Gravity (MHG) reactor (Fig. 1) modified from a household microwave oven system (Samsung ME731K, 2.45 GHz, 800 W). The reactor is equipped with a borosilicate glass tube (capacity 500 mL) as a reaction chamber that is connected to a stainless-steel Liebig condenser via a heat-resistant quartz pipe. The condenser is connected to a circulating water-cooling system (10°C) to accelerate the condensation of oil and water vapors.

The condensed products are stored by gravity in a separatory funnel until they separate into two phases: the essential oil phase (supernatant) and the condensate water phase (infranatant). To ensure power safety and precision, each test is measured using a *digital wattmeter* (Yokogawa WT210) and a K-type thermocouple mounted on the outer wall of the reactor to monitor the reaction temperature.

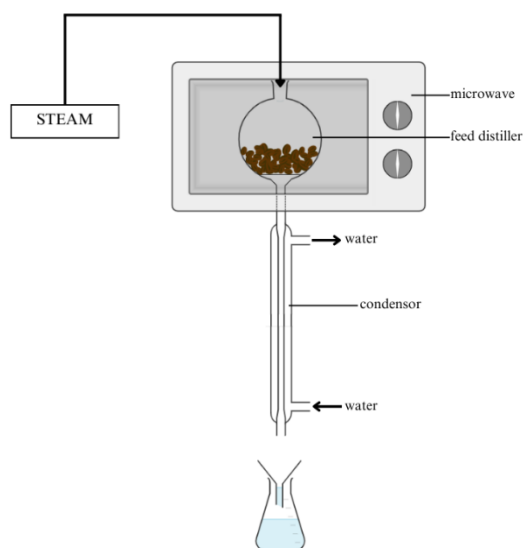


Figure 1. MHG equipment scheme for onion extraction

### Experimental Design

The study was conducted with two main operating variables, namely microwave power (300, 450, and 600 W) and extraction time (10, 20, 30, and 40 minutes). Each combination of treatments is repeated three times to improve the reliability of the data. A total of 100 g of onions is fed into the MHG reactor without the addition of external water. The process begins as soon as the microwave system is activated until the specified time. During extraction, the water vapor and volatile oil formed rises to the top of the reactor and condenses into a liquid mixture that flows into the reservoir by the force of gravity. Oil yield is calculated with the following equation:

$$Y(t) = \frac{m_t}{m_0} \times 100\%$$

With  $Y(t)$  = oil yield (%),  $m_t$  = mass of essential oils obtained at time  $t$  (g), and  $m_0$  = mass of dry matter. After extraction, the oil is dried using anhydrous  $\text{Na}_2\text{SO}_4$  to remove traces of water, then stored in a dark bottle at 4°C before further analysis.

### Extraction Kinetics

Two kinetic models—first-order and second-order—were employed to explain the extraction kinetics of bioactive compounds from onion bulbs, each representing distinct mass transfer mechanisms (Table 1). The first-order model assumes that the extraction rate is proportional to the concentration of unextracted solute and decreases exponentially as equilibrium is approached, indicating a diffusion-controlled process. The hyperbolic model describes a surface-controlled mechanism, where extraction proceeds rapidly at the beginning and gradually slows down following a saturation curve, emphasizing the role of external mass transfer and surface desorption. Meanwhile, the power law model expresses extraction yield as an exponential function of time, suitable for heterogeneous systems dominated by diffusion; its exponent  $n$  characterizes the rate behavior, with  $n < 1$  signifying internal diffusion limitations,

$n = 1$  indicating a constant rate, and  $n > 1$  reflecting structural breakdown that enhances solute release. Collectively, these models provide complementary insights into the dynamics of solute transfer and the mechanisms governing extraction efficiency.

Table 1. Summary of Kinetic Models for Onion Bulb Extraction

Model	Equation	Kinetic Parameters
First-Order	$q_t = (1 - e^{-k_1 t})$	$k_1$ (min <sup>-1</sup> ): rate constant for first order. $q_t$ (mg/g): yield
Second Order	$q_t = \frac{k_2 t}{1 + k_2 t}$	$k_2$ (min <sup>-1</sup> ): rate constant for second order. $q_t$ (mg/g): yield

### Test Parameters

Parameters ( $k_1$  and  $k_2$ ) are obtained through non-linear regression by minimizing the Root Mean Square Deviation (RMSD) value using *Microsoft Excel Solver*. The model with the smallest RMSD value is considered to be the most consistent with the experimental data (Katsampa et al., 2015; Mahfud Mahfud et al., 2022)

## RESULT AND DISCUSSIONS

### Extraction with Microwave Hydrodiffusion and Gravity (MHG)

The extraction process using the Microwave Hydrodiffusion and Gravity (MHG) method depends on the ability of the polar molecules inside the material to interact with oscillating electromagnetic fields. Microwaves cause water molecules and ions inside plant tissues to vibrate intensely, resulting in friction between particles that convert electromagnetic energy into heat energy (*dielectric heating*) (Chemat et al., 2012). The increase in internal temperature causes the vapor pressure in the cell to increase until the cell wall ruptures, releasing essential oil components onto the tissue surface. The resulting water vapor and oil are then pushed upwards naturally by gravitational forces and internal pressure, without the need for a vacuum system or additional solvents. This process allows for quick and efficient oil extraction, while maintaining the integrity of volatile compounds

The presence of water in *the Allium cepa* tissue plays a dual role: as a *microwave absorber* and as a steam transport medium. Water heats up much faster than the non-polar cell wall, creating a pressure gradient that accelerates the diffusion of oil along with water vapor through the pores of the tissue. This phenomenon makes MHG more efficient than conventional distillation, because heating occurs volumetric and directly throughout the material.

### Effect of Material Size on Essential Oil Yield

Material size is a key parameter that affects the efficiency of microwave heating and the rate of oil diffusion out of the plant tissue. In this study, three variations of onion cut sizes were used, namely 1 cm, 2 cm, and 3 cm, both in fresh and dry conditions. The observation results (Fig. 2) showed that 1 cm material produced the highest yield, 4.61 % for dry materials and 1.81 % for wet materials, respectively. While the size of 2 cm and 3 cm produces a lower yield. This shows that the smaller the size of the material, the larger the surface area exposed to the microwave field, so that energy absorption and internal heating take place more evenly.

The small particle size shortens the diffusion distance of oil to the surface, increasing the rate of oil release to the vapor phase.

These findings are in line with research Jahongir et al., (2019) and Yuniati et al. (2024) which suggests that the decrease in ingredient size increases the yield of essential oils due to higher energy transfer and diffusion efficiency. In addition, the water content in the material also affects the extraction results. Fresh onions with high moisture content can undergo hydrolysis of certain volatile compounds during heating, while overly dry ingredients inhibit the formation of internal steam needed to carry oil out. The results of this study indicate that light drying (partial evaporation of water) provides optimal conditions for the MHG process. This phenomenon is consistent with studies Benmoussa et al. (2016) on essential oils *Cuminum cyminum* where the optimum moisture content of 44.67 % yields the highest yield.

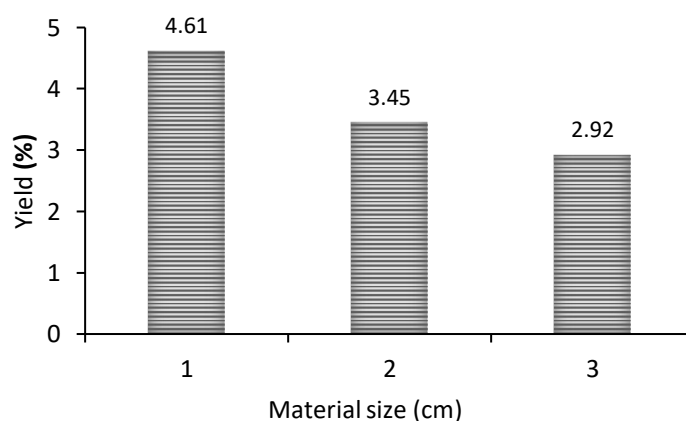


Figure 2. Effect of material size on oil yield (sun drying, 600W, 75 minutes)

The size of the material has an influence on the transfer of energy from the waves *Microwave* which is more even. The smaller the size, the wider the surface that the microwave passes through *Microwave*. The effect of material size on the increase *Yield* has also been done by Jahongir et al. 2019 shows improvement *Yield* with the smaller size of the existing material (Vian et al., 2008).

### **Effect of Extraction Time on Oil Yield**

The duration of extraction has a direct effect on the yield of the oil produced. In general, the longer the extraction time, the more oil is successfully extracted until it reaches a saturated state. Fig. 3 shows that in onions with a size of 1 cm, both in fresh and dry conditions, the yield increases with the extraction time until it reaches a maximum of 75 minutes (600 W). After that point, the increase in time does not provide a significant increase as most of the volatile oils have been released, and the process reaches the equilibrium phase. The kinetics of yield rise show two main phases: (1) the fast phase (0–30 minutes) in which volatile oil escapes due to rapidly increasing internal pressure, and (2) the slow phase (30–75 minutes) in which oil release is controlled by diffusion from the inner tissue. This phenomenon is in line with the kinetic pattern of citronella (*Cymbopogon* sp.) and onion oil extraction (*Allium ascalonicum*) which also shows a two-level profile (Y. Variyana et al., 2019). It should be noted that extending the extraction time above the optimum point can lead to thermal degradation of volatile sulphur compounds, degrading the quality of the oil produced. Therefore, an

optimum time of 75 minutes with 600 W of power was identified as the best operating conditions to obtain maximum yield without significant thermal damage. .

### **Effect of Microwave Power on Extraction Efficiency**

Microwave power is the dominant factor in determining the amount of energy transferred to the material and the process temperature achieved. From the observations, the increase in power from 300 W to 600 W resulted in a significant increase in oil efficiency. At high powers, the vibrations of water molecules and polar ions take place more intensely, increasing *dielectric loss* and generating enough heat energy to accelerate the destruction of the cell wall. This accelerates the release of oil to the steam phase and shortens the time it takes to reach the saturation point.

However, too high a power can cause the phenomenon of local overheating, where some aromatic compounds undergo degradation or polymerization. Therefore, the selection of the optimum power must consider the balance between heating efficiency and the thermal stability of the target compound. These findings are in line with studies by Chemat et al. (2017) and Kusuma & Mahfud (2017) which confirmed that the optimum power for microwave-based essential oil extraction ranges from 450–600 W for <2 cm materials.

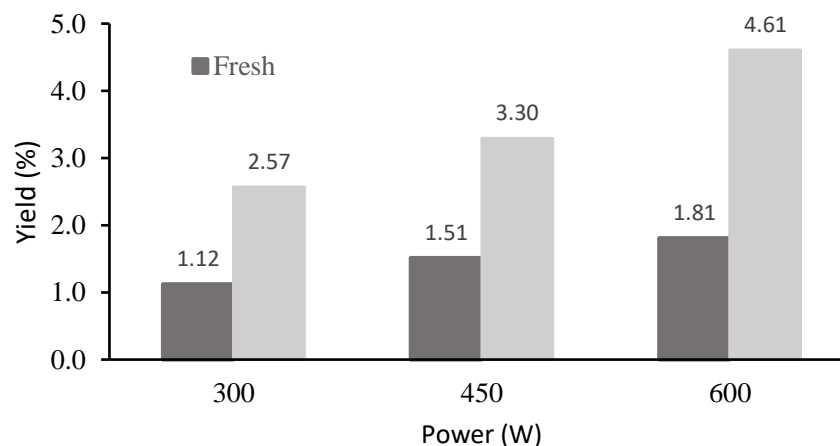


Figure 3. Effect of microwave power on oil yield (1 cm, 75 minutes)

### **Effect of Pre-treatment (Fresh and Dry)**

Pretreatment processes such as light drying or preheating before extraction serve to open the pores of plant tissue and reduce free water content. Fig. 4 shows that dry samples produce higher oil yields (>3.0 %) compared to fresh samples (about 1.5 %).

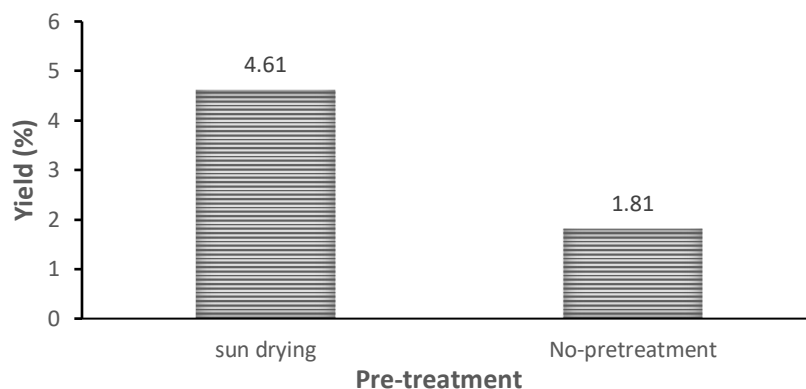


Figure 4. Effect of material conditions on oil yield (600 W, 75 minutes)

This is due to the reduced moisture content which plays a role in reducing the thermal conductivity of the material, so that microwave energy is more focused on the oil component. The drying process also leads to a decrease in internal osmotic pressure, which facilitates the release of oil from the cell matrix (Haqqyana et al., 2020) (Chemat & Cravotto, 2013). These findings are reinforced by Jahongir et al. (2019) and Benmoussa et al. (2008) who report that drying to optimal moisture content improves internal diffusivity and improves extraction efficiency.

Material condition with *Pretreatment sun drying* have *Yield* compared to materials without *Pretreatment* i.e. 4.61 % Process *Sun Drying* helps reduce moisture content in materials so that the radiation process *Microwave* to extract oil Mumbai It is easier to understand that the mass transfer that occurs only carries the mass from the oil. The moisture content should be kept low, as the presence of water can lead to a decrease in oil dissolution in the solvent due to the higher polarity of water than triglycerides, and reduce the mass transfer of triglycerides (Vian et al., 2008) Fig. 4. Effect of material size on *oil yield (sun drying, 600W, 75 minutes)*.

### **Extraction Kinetics Modeling**

To understand the kinetic behavior of the MHG process, oil yield data over time were analyzed using first order and second-order models. The goal is to determine the mathematical model that most accurately describes the mechanism of mass transfer during extraction.

The parameters of the model and are determined through a  $k_1, k_2$  fitting process with a non-linear regression method in the real domain. The difference between the experimental data and the calculation results from the model based on equations (2) or (4) is minimized using the *Root Mean Square Deviation (RMSD) value* through the Solver application in *Microsoft Excel version 2020*. The smaller the RMSD value, the smaller the error rate between the experimental data and the model calculations, which indicates a *good fit* between the two (Kiassos et al., 2009).

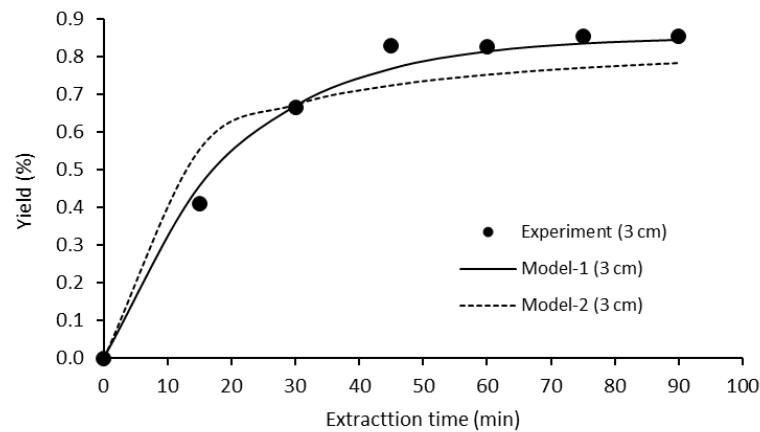


Figure 5. Comparison of two kinetic models with experimental data (fresh, 3 cm, 450W)

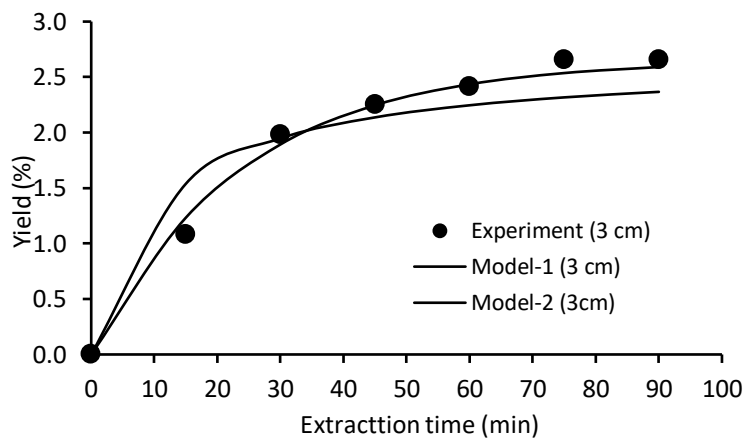


Figure 6. Comparison of two kinetic models with experimental data (dry, 3 cm, 450W)

In the MHG method, the yield of onion oil as a function of extraction time shows a typical pattern: it increases sharply in the early stages of the process, then increases slowly, and finally reaches a near-constant condition. This indicates that the rate of oil release is rapid at the beginning of the process due to the high internal pressure of the dielectric heating, then gradually slows down as the diffusion of oil from the inner tissue becomes the main control stage.

A comparison of the two kinetic models with experimental data for the MHG method is shown in Fig. 5 for fresh materials and Fig. 6 for dry materials. The rate constant values obtained from the modeling as well as the RMSD values at 450 W microwave power are presented in Table 2. Based on this table, the RMSD value of the first-order kinetics model is smaller than the RMSD value of the second-order model, which means that the first-order model is better at representing experimental data of the onion oil extraction process using the MHG method.

These results are in line with previous research on the extraction of citronella oil (*Cymbopogon sp.*) which also showed that first-order kinetics models provide the best results in describing the mechanism of oil release during microwave-based extraction (M Mahfud et al., 2025; Y Variyana et al., 2024) Thus, it can be concluded that the first-order kinetics model

is the most representative model to explain the experimental results of the onion oil extraction process using the MHG method. The extraction rate constant value ( $k$ ) obtained ranges from  $0.03\text{--}0.06\text{ s}^{-1}$ , indicating a rapid oil diffusion rate in the early stages and achieving stability at the end of the extraction process.

Table 2. Obtained kinetic parameters and RMSD values at 450 W power

Condition	Size	$k_1$	$k_2$	RMSD	$R^2$	RMSD	$R^2$
Material	(cm)	(Order 1)	(order 2)	(Order 1)	(Order 1)	(order 2)	(Order 1)
Fresh	1	0.0513	0.0840	0.0531	0.91620	0.1373	0.78352
Fresh	2	0.0593	0.1452	0.0255	0.98368	0.0803	0.94866
Fresh	3	0.0512	0.1454	0.0272	0.99096	0.0743	0.97532
Dry	1	0.0363	0.0212	0.2374	0.96754	0.4414	0.93966
Dry	2	0.0321	0.0265	0.0954	0.99400	0.2296	0.98556
Dry	3	0.0417	0.0347	0.0728	0.99318	0.2223	0.97918

The parameters of the  $k_1$  and  $k_2$  models are determined by adjusting the parameters in the real domain. The difference between experimental data and those calculated from the model via equation (2) or equation (4) is minimized by the mean square root deviation (RMSD) using a solver application (Microsoft Excel 2020 version). Smaller RMSD values indicate fewer errors between the experimental data and those calculated by the model and indicate a good fit between the experimental data and the model (Kusuma et al., 2018). In the MHG method, the yield of onion oil as a function of extraction time increases rapidly at first but then there is a slight increase and eventually it is almost constant. Comparison of two kinetic models with experimental data for MHG presented in Fig. 5 for fresh material and Fig. 6 for drying agent. Table 2 shows that the kinetic parameters were obtained from modeling with RMSD values for 450W MW power. And shows that the value of the 1st order model RSMD is smaller than the 2nd order model RSMD. This shows that model 1 is better at presenting experimental data for the oil extraction process using this MHG method. This is in accordance with the previous for the extraction of citronella oil (*Cymbopogon sp.*) using the best first-order kinetics (Khalili et al., 2018; M. Mahfud et al., 2017). Therefore, the first-order kinetics model represents better results of onion oil extraction experiments than second-order for the onion oil extraction process using the MHG method. Furthermore, the value of the extraction constant is located around  $0.03\text{--}0.06\text{ s}^{-1}$ .

### Evaluation and Interpretation of Kinetic Models

The modeling results are presented in Table 3 and Fig. 5–6. The RMSD values indicate that the first-order kinetic model provides a better fit to the experimental data than the second-order model for both fresh and dried materials. The average RMSD of the first-order model ranged from 0.025 to 0.072, which is considerably smaller than that of the second-order model (0.08–0.44), signifying higher conformity with the experimental results. The rate constant ( $k$ ) ranged between  $0.03$  and  $0.06\text{ s}^{-1}$ , reflecting a rapid diffusion rate during the initial extraction phase followed by a slower rate during the internal diffusion stage. This trend is consistent with the kinetic patterns observed in *Cymbopogon sp.* (citronella oil) and *Allium ascalonicum* (shallot oil), where the first-order model effectively describes the extraction mechanism (Yeni Variyana et al., 2023; Yeni Variyana & Mahfud, 2020). Physically, these findings demonstrate that the release of essential oil during the microwave hydrodistillation (MHG) process is

primarily governed by internal diffusion following first-order kinetics. The early stage is dominated by the rapid liberation of oil from ruptured cell structures, while the subsequent stage is controlled by the diffusion of residual oil through the remaining solid matrix.

Table 3. the comparison of extraction model

No.	Raw Material/Method	Best Kinetics Model	Rate Constant Range (k)	R <sup>2</sup>	RMSD	Reference
1	Onion ( <i>Allium cepa</i> ) – MHG (300–600 W)	First order	0.03 – 0.06 s <sup>-1</sup>	0,95 – 0,98	0,025 – 0,072	This research (2025)
2	Lemongrass ( <i>Cymbopogon nardus</i> ) – MHG	First order	0.028 – 0.055 s <sup>-1</sup>	0,94 – 0,97	0,030 – 0,080	(Mahfud Mahfud et al., 2022)
3	Citrus <i>hystrix</i> – Solvent-Free Microwave Extraction (SFME)	Weibull	$\alpha = 8.1 \text{ min}, \beta = 1.32$	0,98	0,021	(Yeni Variyana & Mahfud, 2020)
4	Cumin ( <i>Cuminum cyminum</i> ) – MHG	First order	0.041 – 0.067 sec <sup>1</sup>	0,95 – 0,99	< 0.05	(Hasnia Benmoussa et al., 2015)
5	Pandan leaf ( <i>Pandanus amaryllifolius</i> ) – MAHD	Order Two	0.0012 – 0.0024 s <sup>-1</sup>	0,89 – 0,93	0,10 – 0,15	(Chemat & Cravotto, 2013)
6	Kitchen lemongrass ( <i>Cymbopogon citratus</i> ) – Hydrodistillation	First order	0.015 – 0.024 sec <sup>1</sup>	0,90 – 0,94	0,12 – 0,19	(Yeni Variyana et al., 2023)
7	Garlic ( <i>Allium sativum</i> ) – Microwave Hydrodistillation	Weibull	$\alpha = 6.7 \text{ min}, \beta = 1.45$	0,97	0,030	(Yeni Variyana & Mahfud, 2022)

The comparative results summarized in Table 3 further show that the pseudo-first-order kinetic model consistently provides the best fit for various natural materials with high moisture content, such as *Allium cepa* and *Cymbopogon sp.* The rate constant ( $k$ ) values obtained in this study (0.03–0.06 s<sup>-1</sup>) are comparable to those reported by Benmoussa et al. (2015) and Variyana et al. (2024), indicating a similar dominant mechanism characterized by internal diffusion control, where the rate of oil release is strongly influenced by the internal water pressure generated by dielectric heating. Conversely, in solvent-free microwave extraction (SFME) systems—such as those investigated by Haqqyana et al. (2020)—the Weibull model provides a more accurate representation, as it accounts for the nonlinear desorption behavior associated with changes in internal viscosity during solvent-free extraction.

The consistently high coefficient of determination ( $R^2 > 0.97$ ) reported across multiple studies confirms the reliability of kinetic modeling in predicting the rate of microwave-assisted essential oil extraction. Overall, the present results support previous literature showing that first-order kinetic models are the most representative for describing the MHG extraction process of high-moisture plant materials. Furthermore, MHG technology has been demonstrated to be more efficient than conventional distillation in terms of energy consumption, processing time, and maintenance of essential oil quality.

## CONCLUSION

This study examines the kinetic model of essential oil extraction from onions (*Allium cepa*) using the Microwave Hydrodiffusion and Gravity (MHG) method as an efficient and solvent-free green technology approach. The results of the study show that MHG is able to extract high-yield essential oils in a shorter time than conventional distillation. Microwave heating results in an even distribution of heat in material tissues, accelerates cell wall damage, and

accelerates the release of volatile oils. The process parameters that have the most influence on oil yield are microwave power, material size, moisture content, and extraction time. The 1 cm material size gives the highest results (4.61 %) at 600 W and 75 minutes. The small size increases the surface area that absorbs microwave radiation, thus accelerating the diffusion of oil. Light drying before extraction also increases yield as it reduces excess moisture content that can lead to hydrolysis of volatile compounds. The optimum power is in the range of 450–600 W, while the optimum time of 75 minutes results in a balance between the heating rate and the stability of the oil compounds. Kinetic analysis showed that the pseudo-first-order model was best suited to the experimental data, with a rate constant ( $k_1$ ) of 0.03–0.06 s<sup>-1</sup> and  $R^2 > 0.95$ , as well as a Root Mean Square Deviation (RMSD) between 0.025–0.072. These results indicate a controlled internal diffusion mechanism, where the initial stage of extraction takes place quickly due to high internal pressure, followed by slow diffusion towards the surface of the material. The MHG method has been proven to be energy-efficient—saving up to 40 % compared to traditional steam distillation—and environmentally friendly because it is solvent-free and has minimal liquid waste. This research confirms the potential of MHG as a modern extraction technology that is efficient, economical, and sustainable. The kinetic model obtained can be the basis for the development of an industrial-scale MHG continuous reactor system for the processing of high-value local aromatic materials.

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