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Kinetic modeling for microwave-assisted green extraction: Effects of power on citronella oil from *Cymbopogon nardus* leaf

Haqqyana Haqqyana, Ali Altway, Mahfud Mahfud*

Department of Chemical Engineering, Faculty of Industrial Technology and Systems Engineering, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia

ABSTRACT

Cymbopogon nardus, known as a native plant to the subtropical and tropical areas, is widely cultivated and utilized for food flavoring and pharmaceutical purposes. Microwave-assisted hydrodistillation (MHD) was preferred as a greener method to extract essential oils. Kinetics of essential oil extraction from *Cymbopogon nardus* leaves were observed under different values of microwave irradiation power at atmospheric pressure. This method facilitated a high yield of citronella oil (3.68%–3.79%) at reduced time. Kinetic investigation of citronella oil extraction process was simulated using mathematic formulation such as pseudo-first and pseudo-second-order models. Results indicated that the studied models provided moderate fit for the experimental data, whereas the latter of the two kinetic models demonstrated better general fit, especially at low power levels. Moreover, GC-MS analysis of the citronella oil showed that the main compounds identified were geraniol and methyl isoeugenol. Other active compounds such as citronellal and β-citronellol were also present in considerable amount. These results suggested that the MHD method could be a prominent alternative to obtain essential oils in higher yields and deliver valuable chemical constituents upon shorter extraction time, compared to its conventional alternatives.

Keywords: Citronella oil, Microwave-assisted hydrodistillation, Kinetic modelling, Cymbopogon nardus leaves, Green extraction.

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Corresponding Author:
Mahfud Mahfud
mahfud@chem-eng.its.ac.id

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1. INTRODUCTION

Essential oils are classified as volatile aromatic component-rich liquids. This type of oils can be derived from various parts of the plant, such as leaves, flowers, and stems. There are approximately 250 types of essential oils from various countries (Rassem et al., 2016). The potential value of the substance as non-oil and gas commodities is highly profitable. Essential oils and their derivative compounds are needed in various industries such as food and beverage, perfumery, cosmetics, as well as pharmaceuticals industries.

Citronella leaves and stems have a lot of industrial potential due to its main volatile aromatic compounds (VACs) such as citronellal, citronellol, geraniol, which provide its characteristic citrus smell that is well-favored. One of the commonly known types of essential oil is obtained from *Cymbopogon nardus (C. nardus)*. This species of *Cymbopogon* plant has been widely cultivated in some of the tropical countries, including Indonesia. Ceylon type citronella oil that is obtained from *C. nardus* contains chemical constituents such as geraniol, citronellal, citronellol, limonene, methyl eugenol, and geranyl acetate (Brito et al., 2021; Kamarulzaini et al., 2020). Citronella oil is known for its antioxidant, antibacterial, and anti-inflammatory properties (Bayala et al., 2020; Wibowo et al., 2018). It has been presumed that the antibacterial activities shown in the oil was due to the presence of geraniol and citral compounds

(Aiemsaard et al., 2021). Moreover, citronella oil is also applicable as a flavor additive for food products. Due to its low sensory threshold, it was reported that geraniol and citronellol are two of the most flavor-active terpenes (Nigam and Pandey, 2009). They also appeared to have insecticidal and repellent activities (Pitija et al., 2014). Furthermore, geraniol and its congeners such as citral and nerol also performed positive effects as agents to protect and preserve foods (Jeon et al., 2009).

With its growing demand in the global market, the prospects of citronella oil production in Indonesia have yet to be sufficiently supported with proper technology development. Until now, Indonesia still tends to export citronella oil in the form of crude oil due to the limitations of the conventional extraction method applied. Studies conducted on the conventional extraction of *Cymbopogon* plants using the water-steam distillation method generally resulted in a low yield of oils (around 0.039%–0.39%) (Zaituni et al., 2016). Research on the distillation of citronella oil derived from *C. nardus* using hydro-distillation (HD) obtained a relatively fair amount of oil yield (~1.5%) (Gavahian et al., 2018). Furthermore, conventional methods have been reported to possess several disadvantages such as large energy and solvent consumption, longer extraction time, VACs degradation, and low extraction efficiency (Zhang et al., 2018).

New methods have been proposed in economical- and environmental-friendly approach for extracting essential oils. One of them is using a microwave as a heating source. Among several extraction methods that are developed, microwave-assisted hydro-distillation (MHD) provides substantial benefits over conventional HD. The application of microwave heating combined with hydro-distillation results in a faster extraction rate, shorter extraction period, and high-quality products without further applying a complicated and costly separation process (Farhat et al., 2017; Kusuma and Mahfud, 2017a; Nitthiyah et al., 2017).

Understanding the effect of microwave power and extraction kinetics can help to ensure maximum extraction efficiency. In MAE, microwave power directly controls the absorption of microwave energy inside the extraction flask that affects sample heating (Xue et al., 2018). Hence, determining the power level to obtain the desired yield with adequate properties must be considered appropriately. The objective of this study is to justify the kinetics of the citronella oil extraction from *C. nardus* leaves. Known kinetic models such as pseudo-first order (PFOM) and pseudo-second order kinetic models (PSOM) are discussed to evaluate the feasibility of the models in representing the actual observation data. The influence of extraction time and microwave power level on the MHD extraction kinetics of *C. nardus* leaf oil is reported. Furthermore, the chemical constituents of the obtained essential oil are identified and further discussed.

2. MATERIALS AND METHODS

2.1 Materials

Cymbopogon nardus leaves used in this study were obtained from Blitar, East Java. The collected leaves were in the form of fresh leaves and dried through aeration for ± 5 days. After, the dried leaves were cut into ± 1 cm.

2.2 Microwave-assisted Hydrodistillation (MHD) Method

A set of equipment needed to extract *C. nardus* essential oil by applying microwave irradiation is a modified domestic microwave oven (R-21D0(S)-IN, Sharp) connected to the Clevenger that passes through a hole at the top of the oven (Fig. 1). The dimensions of the microwave oven have a length of 485 mm, a width of 400 mm, a height of 292 mm with a 2450 MHz wave frequency and a maximum power of 800 W. A single neck round bottom flask was used for distilling to extract essential oil. For all experiments, forty grams of dried *C. nardus* leaves were soaked in a distiller filled with 500 mL of water. The distilling flask was placed inside a microwave cavity and irradiated at various power levels (450, 600, and 800 W). Microwave-assisted hydrodistillation was conducted for 180 min and data were collected for each of 30 min interval until completion. The collected citronella oil yields were calculated using Equation 1:

$$citronella\ oil\ yield\ (\%\ ^{w}/_{w}) = \frac{calculated\ mass\ of\ extracted\ oil}{mass\ of\ dried\ Cymbopogon\ nardus\ leaves} \times 100\% \quad (1)$$

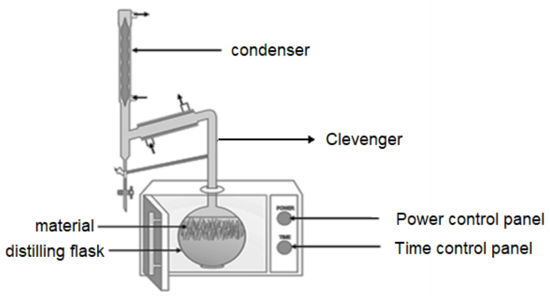


Fig. 1. Schematic diagram of the MHD equipment

2.3 Extraction Kinetic Modelling

Several mathematical and empirical models can be used to describe the extraction process. In this study, the kinetics of citronella oil extraction using the MHD method were calculated by applying the established kinetic models such as PFOM and PSOM. A typical solid-liquid extraction process is controlled by a diffusion mechanism. Model equations incorporating Fick's law are commonly used in solvent extraction modeling because they represent the basic theory of mass transfer (Kim et al., 2002). Simplification of assumptions is made that the main mechanism which controls the extraction rate is the transport of the extracted oil from the surface of the plant particle into the bulk solution and the external mass transfer resistances are negligible. Essential oil is treated as a pseudo-component of constant properties with insignificant changes in composition and/or kinetic constants of the constituents during the process (Benyoussef and Saibi, 2013). Considering the extraction process carried on in a batch process and no chemical reactions take place, hence the mass transfer rate can be expressed in its differential form:

$$\frac{dC_t}{dt} = k_1(C_s - C_t) \tag{2}$$

where k_1 (1/min) is the rate constant value for first-order, C_s is the extraction capacity defined by the citronella oil concentration at saturation (g/L), C_t is the oil concentration at any time (g/L), t (min). Integrating from t = 0 and $C_t = 0$ to t = t and $C_t = C_t$, we obtain the following equation:

$$\ln\left(\frac{C_s}{C_s - C_t}\right) = k_1 t \tag{3}$$

Linearization of Equation (3) allows the equation to be rearranged as follows:

$$\log\left(\frac{C_s}{C_s - C_t}\right) = \frac{k_1}{2{,}303} t \tag{4}$$

The PFOM was determined by a plot of log $(C_s - C_t)$ against t, resulting in the slope and intercept of a linear equation that will be used in determining k_1.

In addition to expressions derived from Fick's law, the adapted second-order rate law has also been employed for extraction modeling (Jabar et al., 2015; Wang et al., 2022). A distinct extraction kinetic for microwave-assisted processes has been highlighted by another report (Lee et al., 2016), owing to its significant increase in the obtained extraction yields at a reduced time as compared to the conventional extraction method. This behavior indicates that a fundamentally different mechanism during microwave heating occurs. Thus, a second-order mechanism was considered to be a plausible approach to describe the kinetics of microwave-assisted extraction, as disclosed in other studies (Kusuma and Mahfud, 2017b; Patil and Akamanchi, 2017). The second-order rate law labeled as PSOM shows that the extraction rate is directly proportional to the square of the oil yield. Hence,

$$\frac{dC_t}{(C_s - C_t)^2} = k_2 dt \tag{5}$$

Integrating from t = 0 and $C_t = 0$ to t = t and $C_t = C_t$, we obtain the following equation after rearrangement:

$$C_t = \frac{C_s^2 k_2 t}{1 + C_s k_2 t} \tag{6}$$

Linearization and rearrangement of Equation (6) to calculate the extraction rate (C_t/t), thus:

$$\frac{C_t}{t} = \frac{1}{\left(\frac{1}{k_2 C_s^2}\right) + \left(\frac{t}{C_s}\right)} \tag{7}$$

where h is the initial extraction rate at $C_t/t \rightarrow 0$, hence $h = k_2 C_s^2$. A plot between t/C_t against t was made to determine the second-order rate constant k_2 (L/g-min) for the PSOM. This formula can be rearranged as the following Equation (8):

$$\frac{t}{C_t} = \frac{t}{C_s} + \frac{1}{h} \tag{8}$$

The linear relationship obtained from t/C_t plotted against t provides the slope and intercept, thus enabling the determination of h, C_s, and k_2 values.

2.4 Statistical Analysis

The validation of each model for citronella oil extraction was evaluated by the coefficient of determination R^2 and root mean squared error (RMSE). The coefficient determination is defined by:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{9}$$

where x_i is the value of citronella oil for observation i obtained from experiment, $\hat{x}_i$ is the mean value, $\hat{x}$ is the predicted value of citronella oil yield for observation obtained from the kinetic models and n is the total numbers of data. As for the RSME, defined by:

$$RSME = \sqrt{\frac{1}{m}\sum_{i=1}^{n}(x_i - \hat{x}_i)^2} \tag{10}$$

where m represents the number of total observations.

2.5 GC-MS Characterization of Citronella Oil

All the significant compositions of citronella oil obtained by MHD were determined by GC-MS analysis. For this application, the Agilent 6890 N Gas Chromatograph (GC) System equipped with an autosampler was coupled to the 5973 inert Mass Selective Detector (MSD). The system was configured with an HP-5 MS column. The GC-TIC chromatograms and mass spectra were acquired using Wiley Library 7.0.

3. RESULTS AND DISCUSSION

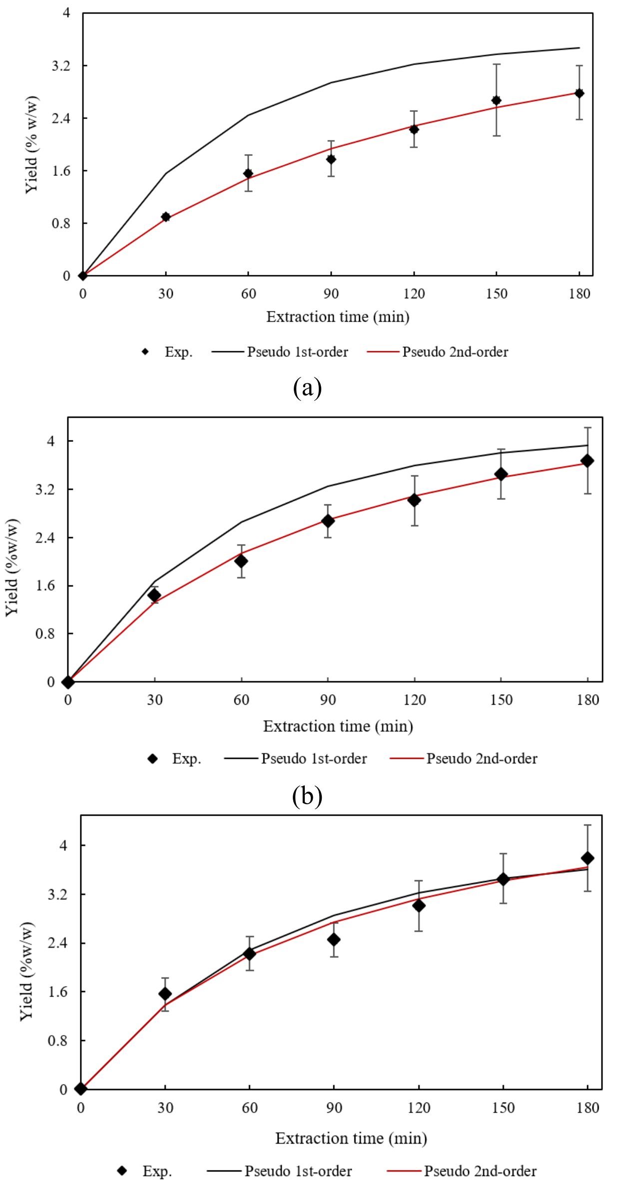
3.1 Kinetic Modelling of Citronella Oil Extraction Using the MHD Method

Citronella oils were extracted using the MHD method by applying three different power levels; 450, 600, 800 W, as the ratio of *Cymbopogon nardus* leaves to water was set at 0.8 g/mL. The kinetic experiments were conducted for 180 min with 30 min intervals under predetermined conditions. Results suggested that the obtained yields would generally surge with the increase in microwave power. The highest citronella oil yield was obtained at 800 W microwave power with 3.79% w/w, followed by 3.68% w/w oil at 600 W and 2.79% w/w oil at 450 W. The rise in power level pursues rapid heating of in situ water inside the plant matrix, which is polar molecules; thus accelerates the rate of extraction (Desai et al., 2010). Fig. 2 also indicated for each experiment under various irradiation power, the obtained yields tend to increase rapidly at the early period of extraction until the increment becomes slightly insignificant at longer irradiation time. Similar results were also reported by other studies (Krishnan and Rajan, 2017; Marković et al., 2019).

The kinetics of the citronella oil extraction was described by two models, namely PFOM and PSOM. In the present study, linear regressions were used to determine the best kinetic models that fitted the observation. The least squares method was applied for discovering the kinetic models' parameters. Values of each kinetic model constants, k_1 and k_2, the extraction capacity, C_s, and the initial rate of pseudo-second order model, h, were tabulated in Table 1. Presented in Table 1 also the values of statistical criteria; the coefficient determination R^2 and RMSE. A kinetic model is best representing the results of experimental data if the R^2 value is close to 1 and the RMSE value is relatively small.

According to the R^2 and RMSE values, both kinetic models exhibit acceptable results. The PSOM had the largest coefficient determination ($R^2 > 0.97$) and the lowest RMSE (< 0.15) for each MHD experiment at various power levels. A good agreement between the experimental data of the citronella oil yields obtained from the MHD method and the predicted oil yields fitted from the kinetic models was illustrated in Fig. 2. Thereby, it can be implied that the extraction kinetic of *C. nardus* essential oils using the MHD method follows the pseudo-second order model relatively better compared to the pseudo-first order. This finding confirms the previous study on citronella oil extraction by various methods including ohmic-heated hydrodistillation, hydrodistillation, and steam distillation, which followed similar second order model (Hamzah et al., 2014). Furthermore, models based on second-order rate has been reported to adequately describe the kinetics of microwave-assisted hydrodistillation of bioactive compounds from Vernonia cinerea leaf (Alara and Abdurahman, 2019).

The results presented generally lower coefficients of determination R^2 for the PFOM as compared to the PSOM under all power levels (Table 1). As shown in Fig. 2, the PFOM exhibits an underfit model of the experimental values, especially at lower microwave power levels (Fig. 2 (a, b)). Thus, it could be implied that the extraction process assisted by microwave radiation does not generally follow the evolution of a first-order kinetic model. As previously discussed by Harouna-Oumarou et al. (2007), also in reference to a study conducted by Ho and McKay (1999), the application of a first-order rate equation is often limited to certain operating conditions. The PFOM more appropriately represents the experimental data for a rapid process that occurs in one mechanism (Covelo et al., 2004). It is apparent that the kinetic data shows the presence of an inflection point as shown in Fig. 2, whereas the extraction process that follows a first-order kinetic rate commonly generates an exponential curve.



(c)

Fig. 2. Comparison of the pseudo-first order (PFOM) and pseudo-second order kinetic model (PSOM) with experimental data on the citronella oil yield at 0.8 g/mL feed-to-water ratio, 180 min, and various microwave power (a) 450 W (b) 600 W (c) 800 W.

Table 1. Kinetic parameters and statistical analysis values at various microwave power

Microwave power (W)	Pseudo-first order				Pseudo-second order				
	C_s (g/L)	k_1 (1/min)	R^2	RMSE	C_s (g/L)	k_2 (L/g-min)	h	R^2	RMSE
450	3.58	0.0191	0.9470	0.7998	4.98	0.0014	0.0352	0.9924	0.0807
600	4.12	0.0173	0.9795	0.4367	5.59	0.0019	0.0578	0.9954	0.0815
800	3.89	0.0147	0.9751	0.1969	5.41	0.0021	0.0617	0.9845	0.1489

It is suggested that the shape of a kinetic curve is associated with operating conditions such as the microwave power level. In microwave extraction, the absorption of microwave energy by the materials inside the extraction vial generates heating that occurs either volumetrically and/or selectively (Taqi et al., 2020). Controlling the microwave power could enhance the efficiency of the extraction process and improve the yield of targeted oils.

The application of PFOM gives predicted results that deviate from the actual yields. An unusual trend of values that is very different from the experimental values was observed. The PFOM kinetic rate constant k_1 decreased with the increase of the microwave power level, yet the extraction capacity C_s showed an increase before being depleted at the highest power level (Table 1). In addition, the predicted values of C_t over time are higher than the actual values, especially at lower power levels. The first-order model is developed based on the assumption of one mechanism which is contrary to the experimental findings in Fig. 2 (a, b). Hence, displaying a poor agreement with the experimental values.

It can be implied from Fig. 2 that the PSOM is able to describe the microwave extraction kinetics relatively better, especially at lower radiation power levels. The introduction of the quadratic term in the second-order rate law model empirically accommodates the effect of microwave heating. Furthermore, the initial rate constant h can disclose the mechanism during the initial step of the extraction process.

Microwaves heating can accelerate essential oil extraction (Flórez et al., 2015). Lee et al. (2016) discussed that the improved extraction yield and rate are due to a temperature-induced diffusion mechanism. The proposed mechanism suggests that selective microwave heating induces gradient in temperature between the plant cells and the bulk solvent of the solvent/plant system. It indicates that mass transport occurs with an additional driving force different from conventional heating extraction (Taqi et al., 2020). When a material is selectively heated, a temperature gradient occurs between the material and its surrounding, and the decrease of chemical potential inside the plant cells occurs. This change in chemical potential leads to solvent diffusion inside the solid matrix, increases the inner cell pressure, and causes cell rupture (Lee et al., 2016). In addition, this effect also enhances the kinetics of the extraction of the accessible solute out of broken cells that corresponds to the initial slope of the kinetic curve (washing step) (Dominguez and Muñoz, 2017; Xu et al., 2021).

The rate of the extraction process is usually determined by the diffusion mechanism as the rate-limiting step. During this period, the solute transport through the plant matrix hence the extraction rate is relatively low. The extraction yield obtained in this step is highly dependent on the intact cells that are present (Crossley and Aguilera, 2001). Particle size reduction and cell wall degradation can enhance internal mass transfer. The microwave heating facilitates the degradation of the cell wall, increasing the extraction yield that can be obtained during the overall extraction process. Fig. 2 (a) indicated that limiting the microwave effect at low power during the extraction does negatively impact the amount of the oil yield obtained in the washing and diffusion stages.

Interestingly, at a high-power level, the application of the PSOM converged to the first-order model. This result implied that as the microwave radiation intensified, the rapid temperature increased inside the extraction vial due to the high absorption of microwave energy. As the cell walls degraded more severely, the initial extraction rate due to washing became faster. These results support previous findings that an improved extraction is due to the plant cell structure disruption induced by microwave heating (Chemat and Cravotto, 2013; Lee et al., 2016). Thus, reducing the diffusion resistance and accelerating the kinetic rate (Rostagno and Prado, 2013).

To better understand the relation of the kinetic parameters to the experimental values, the PSOM parameters were also evaluated. The kinetic parameters shown in Table 1 indicated that the PSOM yielded higher extraction capacity C_s for all conditions. The highest C_s value of 5.59 g/L was observed at 600 W irradiation power, while the experiment conducted at the lowest power value 450 W generates low C_s value. Moreover, the PSOM kinetic rate k_2 shows little change with varying power level. Kusuma and Mahfud (2017b) suggested that based on the second order kinetic model expression, the extraction capacity C_s has a prominent effect than the kinetic rate constant k_2. Similar findings were also reported by previous researchers (Alara and Abdurahman, 2019). Although the change in values is slightly insignificant, it still can be observed that the PSOM kinetic rate constant k_2 increased with rising microwave power. This result further approves that higher microwave power likely generates higher energy absorption by the materials (Megawati et al., 2019). Thus accelerating the extraction kinetic rate.

Moreover, increasing the power above 600 W shows a decrease in the C_s value. It can be observed from Fig. 2 that a rising power level up to 800 W only provides a slight increase in the total oil yield obtained at the final extraction time. Further observed, the oil yield obtained at 800 W for the 90 min was even lower (2.45% w/w) when compared to the one obtained at 600 W (2.67% w/w). Intriguingly, the extracted oils over a longer extraction time at 600 W (within 120 and 150 min) were close to that observed at 800 W.

Following this result, it has been noticed that the h value increases with increasing power level and thus indicates the rate at the start of extraction is faster at the higher irradiation power. This finding has been corroborated by the results shown in Fig. 2. Compared to MHD extraction at a low power level of 450 W, the graph line at the same MHD extraction of *C. nardus* leaf oil but at a higher power level has a steeper gradient at the beginning. The obtained yield at the initial stage under the lowest power of 450 W was limited compared to higher power levels. The extraction rate at low irradiation gradually changes over time. Thus, applied low irradiation needs a longer extraction time to extract more oils. Rising the level of power from 450 to 600 W did show an improvement in oil yields. However, as previously indicated, exposure to the highest power level of 800 W displayed a fair result. Prolonged period of extraction upon higher power level might result in yield reduction as shown in this study. The excessive local heating possibly caused thermosensitive compounds to degrade thus affecting the extraction yield (Ismail-Suhaimy et al., 2021). Accordingly, the 600 W power level is considered favorable for the current study.

3.2 The Compositions of the Citronella Oil Identified by GC-MS

Table 2 summarized the chemical composition results of the citronella oil isolated from *Cymbopogon nardus* leaves. Out of the oils obtained from this study, 34 compounds were detected including 5 unidentified compounds. The citronella oil was characterized by rich monoterpenes content (77.63%), of which the oxygenated monoterpenes were the most dominant (67.98%) followed by monoterpenes hydrocarbons with 9.65%. It was noted that sesquiterpenes hydrocarbons and oxygenated sesquiterpenes presented in lower percentage, accounted for 2.23% and 4.95% of the total chemicals, respectively. High level of oxygenated compounds is preferred, since it is responsible for the odorous properties of essential oils (Flórez et al., 2015).

Among the monoterpenes that were found, geraniol is the most significant volatile compound with 39.20%. Citronellal (9.67%), and β-citronellol (9.49%) were the other primary monoterpenes alcohol found in this work. Previous studies presented similar result regarding geraniol, citronellal, and citronellol as the main chemicals of *Cymbopogon sp.*-derived oil (De Toledo et al., 2016; Saputra et al., 2020). Other studies showed that the predominant compound found in *C. nardus* derived oil is geraniol (Wany et al., 2013), with richer geraniol content can be found in the oil of *C. nardus* plant that was harvested after five months old (Chong et al., 2015). A phenylpropanoid namely methyl isoeugenol was present (11.19%). Methyl isoeugenol is commonly found as one of the main components in the essential oil of *C. nardus* (Wany et al., 2013). It is a natural food flavor agent that shows anxiolytic and antidepressant properties (Fajemiroye et al., 2014). Other compounds such as DL-Limonene, β-Ocimene, (1S)-2,6,6-Trimethylbicyclo[3.1.1]hept-2-ene, (Z)-Citral, geranyl acetate, geranyl butyrat, and elemol were presented in an amount of more than 1%.

Table 2. The chemical compounds of the citronella oil derived from *C. nardus* leaves as identified by GC-MS analysis

No.	*Compound Name*	*Normalized Area (%)*
	Monoterpene Hydrocarbon	
1	DL-Limonene	4.91%
2	(1S)-2,6,6-Trimethylbicyclo[3.1.1]hept-2-ene	3.32%
3	β-Ocimene	1.42%
	Oxygenated Monoterpenes	
4	(-)-Isopulegol	0.28%
5	Citronellal	9.67%
6	beta-Citronellol	9.49%
7	Z-Citral	3.35%
8	Geraniol	39.20%
9	Geranyl formate	0.28%
10	Geranyl acetate	2.60%
11	Geranyl butyrat	2.17%
12	Geranyl hexanoate	0.33%
13	Linalool L	0.61%
	Sesquiterpene Hydrocarbon	
14	β-Elemene	0.35%
15	trans-Caryophyllene	0.20%
16	α-Bergamotene	0.43%
17	Germacrene-D	0.99%
18	1,2,2-trimethyl-1-(P-tolyl)-cyclopentane	0.26%
	Oxygenated Sesquiterpene	
19	Elemol	3.82%
20	Farnesol	0.11%
21	Caryophyllene oxide	0.23%
22	ɣ-Eudesmol	0.30%
23	α-Eudesmol	0.49%
	Misc. Compounds	
24	2,6-dimethyl hept-5-en-1al	0.35%
25	Rose furan	0.21%
26	2,6-dimethyl-5-Hepten-1-ol	0.66%
27	Rose furan epoxide	0.24%
28	Cis-2,6-dimethyl-2,6-octadiene	0.62%
29	Methyl isoeugenol	11.19%
30	*Total not identified*	1.94%

4. CONCLUSION

In this study, the kinetics of citronella oil extraction derived from *Cymbopogon nardus* leaves using the MHD method were conducted, and the results were fitted to two kinetic models. The established kinetic models were applied to the experimental data for determining the extraction kinetics at various power. The results suggested that the extraction of citronella oil from *C. nardus* leaves using the MHD method acts following the pseudo-second order kinetic models relatively better, especially at lower power level. This finding suggests that microwave heating sufficiently effect the mechanism and the kinetic rate of essential oil extraction. Moreover, the chemical characterization results confirmed the potential value of the essential oil obtained for further industrial purposes due to the high content of valuable volatile compounds such as geraniol and citronellal.

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