



Research article

Optimization and kinetic study of biodiesel production from nyamplung oil with microwave-assisted extraction (MAE) technique

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HIGHLIGHTS

- The Optimum condition for power of microwave and extraction time with response surface methodology (RSM).
- Rate constant estimation of 1st, 2nd and 3rd order from purification process nyamplung crude oil at various power.
- The activation energy result for microwave assisted extraction method (MAE).

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ABSTRACT

Nyamplung oil (*Calophyllum inophyllum*), which has a high oil content and non-edible, has a lot of potential as a raw material in the production of biodiesel. Therefore, it has no impact on food security. In this research, response surface methodology was used to find the optimum conditions of biodiesel production from nyamplung, and the kinetics model of esterification reaction of free fatty acid (FFA) in the MAE method was determined. This study used RSM with central composite design (CCD) to find the optimal operating conditions. The RSM optimization with TG recovery shows 95.49% and FFA recovery 31.42% with operating conditions respectively at 423 W and 427 W and extraction time for 40 and 38 min. According to kinetic experiments conducted at various microwave power levels, the conversion of nyamplung into biodiesel follows the first, second, and third-order reactions. According to the data, the maximum R^2 is found in the second and third-order reactions. It was determined the activation energy and kinetic rate constants. The reaction rate constants significantly increased at 150, 300, and 450 W, namely 0.0005 mol^{-1} , 0.0008 mol^{-1} , and 0.0008 mol^{-1} . Nevertheless, it drops at 600 W to 0.0004 mol^{-1} . It was found that the activation energy value using the MAE method was 604.43 J/mol. This value was smaller than the value of the activation energy using the conventional method, 4831.26 J/mol. It was shown that biodiesel production from nyamplung oil with the MAE method could change the conventional method because it needs less energy and less time. So, the production process is more efficient.

1. Introduction

Energy availability is a crucial issue since it plays a key part in maintaining a nation's economic machinery and the cycle of human activity. The Indonesian government works with numerous academic institutions to identify a substitute for non-renewable energy (fossil energy), largely sustaining all current activities. Due to the expanding human population, energy charges are rising in our modern world. To maintain environmental stability, fossil energy would be offered a negative charge because it was finite. One of the sustainable and

alternative resources is biodiesel. However, due to the manufacturing process that uses edible oils like palm oil and coconut oil, the production of biodiesel still confronts several challenges (Sathivel, 2005). Using edible oil could create new problems like a competition between food and energy, soil and water used (Santacesaria et al., 2012). As a result, finding a non-edible oil to use as a biodiesel source is necessary. The most important considerations when choosing materials are the oil content and the amount of oil these plants generate (oil yield), so they can be utilized to make biodiesel and have lower production costs (Gui et al., 2008; Kansedo et al., 2009). The level of TG (triacylglycerol), which is

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largely present in oil, is typically used to determine oil content. Nyamplung was one of the materials chosen. Excellent yield and oil content can be found in this substance (Atabani et al., 2013; Aparamarta et al., 2019b). According to Aparamarta et al. (2016), crude nyamplung oil had TG levels of 78.3 percent. Separating and isolating TG with high purity levels, as well as lowering FFA (free fatty acid) levels, are crucial steps in the synthesis of biodiesel.

The highest challenge in using nyamplung crude oil as biodiesel feedstock is a large amount of FFA. According to Rasul et al. (2016), oil with an FFA level above 2% requires pre-treatment before alkaline-catalyzed transesterification can take place. High FFA levels may cause a saponification process that slows down the production of biodiesel, makes it more difficult to separate the ester from glycerine, and reduces biodiesel yields (Thiruvengadaravi et al., 2012). Therefore, the method for TG purification is applied to get the optimization yield of biodiesel.

The most important factor in choosing the TG purification method was the activation energy. The higher yield is attained the lower the activation energy makes (Shuit and Huat, 2015). Many methods were suggested to achieve a reduced activation rate, including transesterification using s-MWCNTs (Shuit and Huat, 2015), KOH (Darnoko and Cheryan, 2000), and H₂SO₄ catalysts (Berrios et al., 2007). Researchers discovered that the activation energies were 45.80 kJ/mol, 147.70 kJ/mol, and 50.75 kJ/mol, respectively. However, because the activation energy is still larger, a different approach is required to reduce it.

FFA and TG were separated using a multi-stage batchwise solvent extraction (BSE) technique by Aparamarta et al. (2019a), which produced a product with FFA and TG levels of 0.35 percent and 98.53 percent, respectively. The product complied with both domestic and international feedstock requirements for biodiesel production. However, the extraction procedure required a substantial amount of solvent and took six days. The extraction time must be shortened as a result. Lowering it makes the manufacturing of biodiesel more economical and effective.

The microwave-assisted extraction (MAE) method was added to the TG purification procedure in this study. The idea behind this development was to use heat to speed up the separation process and solve its slowdown issue. The fatty acid composition of *C. inophyllum* oil changes as a result of the microwave energy since it can lead to hydrocracking, dehydrogenation, and cracking (Beneroso et al., 2017). Aparamarta et al. (2019a) separated TG and FFA using an MAE approach, resulting in a TG content of 83.46 percent and an FFA content of 7.5 percent.

The amount of solvent required, and the time needed to extract 99 percent of the data are both significantly decreased by this method. The microwave's performance is mostly influenced by the power of microwave and time of extractions (Aparamarta et al., 2020). The more microwave power used, the higher the yields and faster the production. The operating temperature will be high when a lot of microwave power is used, leading to faster yields (Leonel, 2015). The chemical makeup of mace essential oil is also influenced by the temperature of the extraction process (Fernández et al., 2001). Megawati et al. (2019) investigated how power affected essential oil output. The optimum power was at 600 W. The largest essential oil production was seen for this variable, whilst the lowest essential oil yields were observed at 800 W of power. Possible reasons for a decline in essential oil yields include the biodegradation of the oil's constituent parts. However, less research was done to optimize biodiesel production from *C. inophyllum* with MAE methods.

Therefore, this study is to get optimum extraction results in the MAE method. Several factors influence biodiesel production in the MAE method, such as the power of the microwave and the time of extraction (Aparamarta et al., 2020). Using an effective experimental design, the combined interaction of processing factors could be tuned to provide the desired outcome. RSM (response surface methodology) is a valuable tool for designing experiments, building models, analyzing the impacts of variables, and determining the best conditions (Montgomery, 2013). RSM was used by Ghadge and Raheman (2006) to optimize the acid

pre-treatment parameters for making biodiesel from mahua oil. In this work, RSM was used to optimize variables in a purification experiment for *C. inophyllum*. Transesterification kinetics modelling was also investigated. The previous work described a technique based on the utilization of *C. inophyllum* oil as a low-cost feedstock and the effects of various operating parameters such as the solvent to crude oil molar ratio, the methanol to petroleum ether molar ratio, microwave power, and extraction time. At optimal operating conditions, the kinetic constant and activation energy for the transesterification reaction was also established.

2. Materials and methods

2.1. Material

Crude *C. inophyllum* oil (CCIO) was bought from Koperasi Jarak Tani in Klaten, Indonesia. Thin-layer chromatography (TLC) aluminum plates were obtained from Merck in Darmstadt, Germany. Standard triolein, tripalmitin, and fatty acids were purchased from Sigma Chemical Company in St. Louis, MO. All reagents and solvents were either analytical-grade or high-performance liquid chromatography (HPLC)-grade was bought from commercial sources.

2.2. MAE method

MAE was employed for TG purification as defined by Aparamarta et al. (2019a). The variables of this method were crude to solvent ratio = 20% and the solvent mixture between methanol (ME) and petroleum ether (PE) with a comparison of ME: PE = 1:3. After crude and solvent were stirred, the mixture was put into a single neck flask with a specific power (150; 300; 450; and 600 W) and time (30; 60; and 90 min). Gas chromatography (GC) and TLC were used to characterize the data.

2.3. Batchwise solvent extraction (BSE)

This study used two solvents: polar solvent (methanol) and non-polar solvent (petroleum ether). The mass ratio of CCIO and solvent was 1:5, and the mass ratio of polar solvent and non-polar solvent was 1:3. A mixture of solvent was added to CCIO. Afterward, it was stirred (300 rpm) at room temperature for 15 min, then transferred to the separatory funnel. Aparamarta et al. (2016) described the extract as separated and concentrated to give the non-polar lipid fraction (NPLF). The extract of methanol was designated as polar lipid fraction (PLF). The NPLF was purified using methanol at room temperature. The adding of methanol to the NPLF fraction was done in eight stages.

2.4. Biodiesel production using transesterification method

Aparamarta et al. (2020) explained this procedure. ME was added to TG Purified in a 1:8 M ratio. The catalyst was KOH, which accounted for 1.25% of the oil mass. The reaction was carried out at 60 °C for 120 min with steady stirring at 200 rpm. It developed into a two-layer liquid. FAME and methanol were part of the upper layer that was separated using the PE-ME solvent. The top layer was heated to 65 °C in order to evaporate the ME. To get rid of the catalyst, the FAME was gently rinsed with distilled water (DW). The pH of the drained water was adjusted till it was the same as the DW before washing again with distilled water.

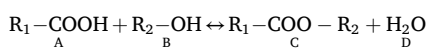
2.5. Response surface methodology (RSM) analysis

With a central composite design (CCD), RSM was used to optimize the process variable to enhance the TG purification of *C. inophyllum* oil in this work. This approach is an excellent design for fitting a quadratic surface model in sequential experimentation. CCD can give helpful information for determining appropriateness (Muthukumar et al., 2017). The regression model was formulated, and the experimental results were

analyzed with the Design Expert 9.0.3 trial version. In the purification of TG, two independent variables were chosen: microwave power and extraction time. As a result, Table 2 shows the models created with the CCD matrices of 32 experiments encompassing the full design of four factors. Multiple regression analysis was used to determine the coefficients. Analysis of variance (ANOVA) was applied to know the significance of the data through adequate precision ratio (p -value < 0.05) (Montgomery, 2005).

2.6. Model kinetic

Esterification reaction is the name given to the kinetic process occurring in the microwave FFA reduction system. The high TG level in the *C. inophyllum* oil is made possible by the lowering of FFA content (Aparamarta et al., 2019a). Excessive methanol is assumed to be the cause of this reaction for irreversible purposes. The rate of the reaction was unaffected by variations in the methanol concentration under these circumstances (Muthukumaran et al., 2017). The purification CCIO's esterification reaction is:



The esterification reaction of CCIO purification is reversible, the rate equation is shown by Eq. (1).

$$r = -\frac{d[A]}{dt} = k_1[A][B] - k_2[C][D] \quad (1)$$

Because this work is aimed at an FFA reduction and TG increase, the reaction is maintained in the direction of the product (TG). So the reaction rate can be written in Eq. (2) as follows.

$$r = -\frac{d[A]}{dt} = k[A] \quad (2)$$

2.7. High-temperature gas chromatography (HT-GC)

The equipment and method of the HT-GC analysis of the sample are as described by Aparamarta et al. (2018). The sample was dissolved in ethyl acetate, then one μL of the sample was injected into the GC. The column's temperature was started at 80 °C, increased to 365 °C with a rate of 15 °C/min, and held for 8 min at 365 °C. The detector's and injector's temperature were both set at 370 °C.

2.8. Thin layer chromatography (TLC)

The TLC analysis was performed in accordance with Aparamarta et al. (2016). The samples stained the TLC paper, which was then submerged in a mobile phase with the ingredients hexane, ethyl acetate, and acetic acid at a ratio of 90:10:1 (v/v/v) until the mobile phase reached the target region. A silica gel and iodine mixture were used to colour the TLC paper. The TLC paper was then exposed to UV light at a wavelength of 366 nm.

3. Results

3.1. Effect of MAE method for TG purification

This study applied the MAE method to purify TG in the seed of CCIO. To increase the solvent's penetration into the sample, this technique was based on the solvent heating theory, which states that polar molecules may absorb microwave energy. Because MAE can save solvents, is quick to extract, and effectively uses energy, it has been used for many different types of organic component extraction (Duarte et al., 2014). Due to its quicker extraction times and use of less solvent than the alternative method, this procedure was considered a green technology as can be seen in Table 1.

Table 1. The comparison between MAE and BSE.

Parameter	BSE	MAE
Extraction time	6 days	30 min
Amount of solvent	600 mL	200 mL

Table 2. Central composite matrix design with a response to experimental results and predictions on the MAE method.

Run	Power (W)	Time (min)	TG Purify (%)	TG Recovery (%)	FFA Purify (%)	FFA Recovery (%)
1	450	45	90.07	94.64	7.35	34.48
2	300	60	87.47	91.5	7.87	36.78
3	600	45	85.79	90.92	8.46	40.02
4	600	30	84.14	91.02	8.21	39.67
5	150	20	77.96	76.82	15	65.95
6	150	60	78.55	83.37	12.67	60.04
7	600	45	85.79	90.92	8.46	40.02
8	150	45	79.85	83.86	11.14	52.25
9	450	60	86.09	93.19	8.18	39.54
10	600	20	80.89	88.82	8.14	39.9
11	300	20	86.67	92.9	8.67	41.51
12	300	45	88.79	94.37	7.5	35.6
13	600	60	81.76	87.9	10.96	52.62
14	600	20	80.89	88.82	8.14	39.9
16	150	20	77.96	76.82	15	65.95
17	150	60	78.55	83.37	12.67	60.04
18	450	20	86.09	93.19	8.18	39.54
19	450	30	88.79	91.97	7.89	36.5
20	450	20	86.09	93.19	8.18	39.54
21	150	30	82.08	83.42	13.01	58.96
22	450	30	88.79	91.97	7.89	36.5
23	450	45	90.07	94.64	7.35	34.48
24	150	30	82.08	83.42	13.01	58.96
25	600	30	84.14	91.02	8.21	39.67
27	300	60	87.47	91.5	7.87	36.78
28	300	30	87.01	91.83	7.98	37.62
29	600	60	81.76	87.9	10.96	52.62
30	450	60	89.06	90.28	7.87	35.62
31	150	45	79.85	83.86	11.14	52.25
32	300	20	86.67	92.9	8.67	41.51

In this study, MAE was applied. As shown in Figure 1, this method was implied to change the degumming, neutralization, and bleaching processes of the refined vegetable oil production. The results of this method have demonstrated the effectiveness of TG purification for biodiesel production.

Figure 2 illustrate the GC and TLC characteristics of the MAE product. Figure 2A is the representation of the TLC result showed that the separation procedure was successful. This successful separation points to the establishment of two layers, with non-polar lipid fraction (NPLF) in the upper layer and polar lipid fraction (PLF) in the bottom layer. The NPLF needs to be refined further because it still contains a limited number of polar molecules. The GC result also supports the same conclusion drawn from Figure 2B. The similar outcome was reported by Aparamarta et al. (2018), who identified PLF and NPLF as the two layers that had been separated using multi-stage batchwise solvent extraction.

The experimental results of the TG purification are shown in Table 2. The experimental data suggest that the FFA and TG contents range between 15% to 7.35% and 77.96%–90.07%, respectively. Table 2 shows that for the variable of 450 W and 45 min, the content of FFA drops from 15.21% to 6.91%, while TG increases from 67.02% to 84.45%. MAE just

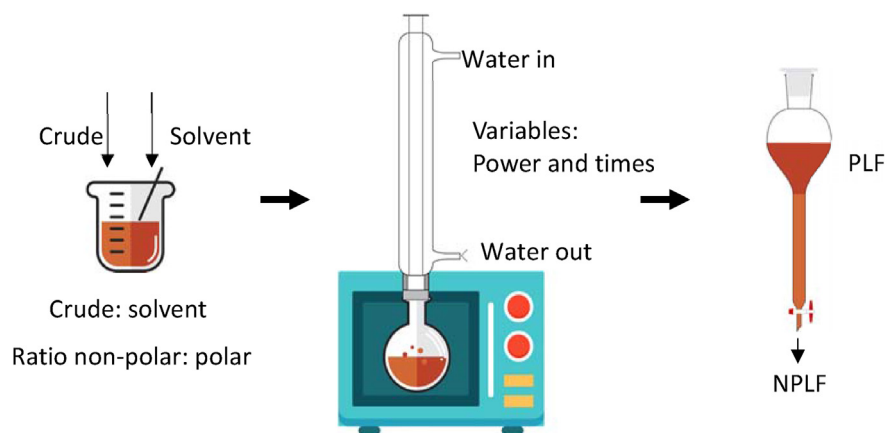


Figure 1. The scheme of microwave-assisted extraction.

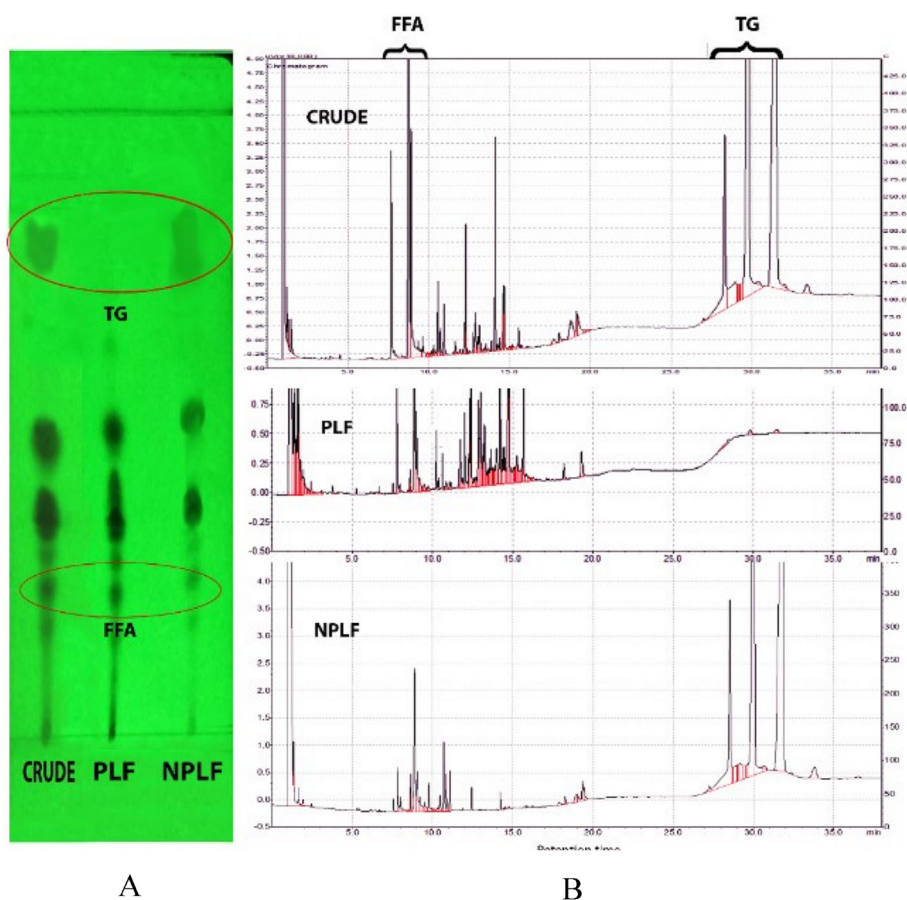


Figure 2. MAE results for the variable of 450 W and 45 min utilizing (A) TLC analysis and (B) GC analysis.

needs 45 min and 2 h of separation time to achieve this consequence. This finding agrees with Aparamarta et al. (2020), who utilized a 30–90 min time variable but showed a more precise value for more variables used.

3.2. Response surface methodology (RSM)

The existing data will be optimized using the response surface methodology (RSM) method with a central composite design (CCD) matrix. As indicated in Table 2, the experimental development design matrix was simulated using the Design Expert 9.0.3 trial version software. A single replicate of the factorial design was used, which is an

experimental design with two components at varying levels: (A) microwave power (150, 300, 450, and 600 W) and extraction (20, 30, 45, and 60 min). In random order, 32 runs were applied. The purity and recovery of TG and FFA were the responses.

In addition, the integrity of the model fit for recuperation of TG and FFA was checked to utilize a typical likelihood plot found in Figure 3A-B, respectively. It tends to be presumed that the two plots were straight lines related to an ordinary conveyance.

Tables 3 and 4 show the ANOVA results of TG and FFA recovery. The p-value is used to express the statistical significance of each variable. It is shown that the time of extraction variable is insignificant (p-value > 0.05), while the power variable is significant for the response to the TG

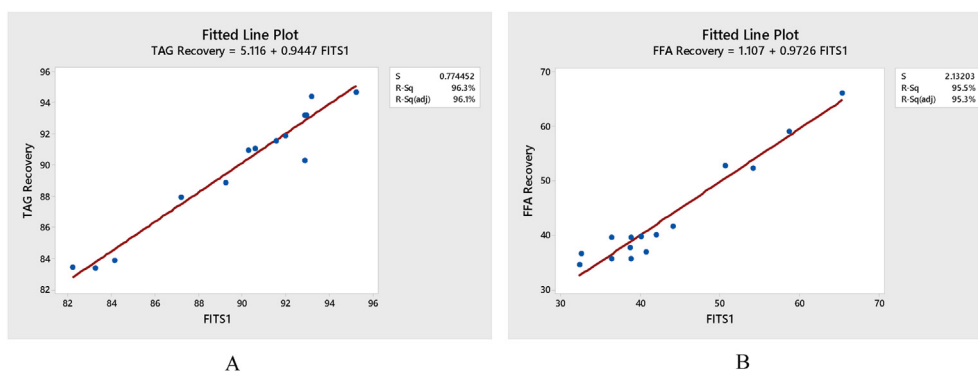


Figure 3. Normal probability plot on TG recovery (A) and FFA recovery (B) based on the RSM.

Table 3. Results of analysis of variance (ANOVA) of TG recovery.

Source	DF	Adj SS	Adj MS	F-Value	p-value	Remarks
Model	5	679.960	135.392	53.20	<0.001	Significant
Linear	2	214.215	107.107	42.08	<0.001	Significant
Power	1	210.344	210.344	82.64	<0.001	Significant
Time	1	3.871	3.871	1.52	0.229	Insignificant
2-Way Interaction	1	22.367	22.367	8.79	0.006	Significant
Power*Time	1	22.367	22.367	8.79	0.006	Significant
Error	26	66.175	2.545			
Lack-of-Fit	10	61.941	6.194			
Pure Error	16	4.234	0.265			
Total	31	743.135				

Table 4. Results of the analysis of variance of FFA recovery.

Source	DF	Adj SS	Adj MS	F-Value	p-value	Remarks
Model	5	2889.69	577.94	81.97	<0.001	Significant
Linear	2	908.46	454.23	64.43	<0.001	Significant
Source	DF	Adj SS	Adj MS	F-Value	p-value	Remarks
Power	1	907.41	907.41	128.70	<0.001	Significant
Time	1	1.04	1.04	0.15	0.703	Insignificant
2-Way Interaction	1	191.40	191.40	27.15	<0.001	Significant
Power*Time	1	191.40	191.40	27.15	<0.001	Significant
Error	26	183.31	7.05			
Lack-of-Fit	10	175.63	017.56			
Pure Error	16	7.68	0.48			
Total	31	3073.00				

and FFA recovery (p -value < 0.05). To see the best TG and FFA recovery model, it can use a normal probability plot shown in Fig. 3A–B. At TG recovery, the value of the coefficient of determination (R^2) is 0.963, and the FFA recovery value is R^2 0.955. From these results, the value is close to 1, with a high correlation between the observed and hypothesis.

For further investigation, three-dimensional plots of the response surface between two independent variables were implied. In comparison, the two other independent variables were maintained at an optimal level to know the interactive effects of factors on the TG purification in the *C. inophyllum* oil. The TG and FFA recovery were applied as the parameter of this works. Figure 4A shows the interactive effect of extraction time and power in TG recovery results in 200–450 W power on the MAE method. The lowest content of TG recovery was obtained at a power of 150 W with an extraction time of 20 min, while the TG recovery content was obtained at 76.8%. The highest content of TG recovery (94.64%) was obtained at 450 W and extraction time of 45 min. The effect of extraction time and power on FFA recovery content is shown in Figure 4B. The

minimum content of FFA recovery (34.48%) was observed at 450 W and extraction time of 45 min. On the other hand, the maximum FFA recovery content (65.95%) was obtained with 150 W and an extraction time of 20 min.

From the response surface plots, it can be shown that TG recovery content increased in line with an increase in the power from 200 W until 450 W. After 450 W, the TG recovery was decreased. The same result occurs in FFA recovery. From Figure 4B, FFA recovery had decreased when microwave power was applied from 200 until 450 W. However, the FFA recovery was increased at the microwave power above 450 W. These results agree with a previous study performed by Aparamarta et al. (2019a), which showed a similar pattern where the TG recovery was decreased at 450 W above that, and the FFA recovery was increased. The higher power makes microwave energy emitted larger so that it makes the degradation of the material and oil components. Tremendous energy received by the material to be converted into heat so that the reaction cuts the triglyceride compound ester bonds (TG) from the oil nyamplung will be bigger, making the TG turn into FFA so FFA increases (Erliyanti and Rosyidah, 2017).

3.3. Optimal TG purification and model validation

The TG purification factors were optimized using Design Expert (DOE) 9.0.3 trial version, as seen in Figure 4. The highest value for TG recovery and the minimum value for FFA recovery were chosen as the target criteria. The best results were obtained at 450 W of power and 45 min of extraction time (TG recovery was 94.64% and FFA recovery was 34.48%), as can be seen from this step. This ideal state was achieved with a 25% methanol concentration and a solvent to oil ratio of 5, as TG is non-polar. This outcome is remarkably similar to the earlier research. The best percentage of TG and FFA recovery was reported by Aparamarta et al. (2019a) at 450 W and 30 min. The percent of TG were 83.46% and 7.50%, respectively.

3.4. The kinetic study of TG purification in MAE method

The reaction rate is usually measured by looking at the change of reactant concentration each time. The rate reaction in the purification of FFA into TG used first-order reaction (Montgomery, 2005). Like the esterification reaction mentioned above, with the amount of methanol used in excess, the concentration of B has no effect. As in Eq. (2), the rate equation for the reaction can be written as Eq. (3) below

$$R = \frac{d[A]}{[A]} = -kt \quad (3)$$

A kinetics study was carried out using FFA conversion data with time variables (20, 30, 40, 60 min) and power variables (150, 300, 450, 600 W) to find the rate constants. The 1st, 2nd, and 3rd order rate constants are described in Table 5. The data have shown that the highest R^2 is

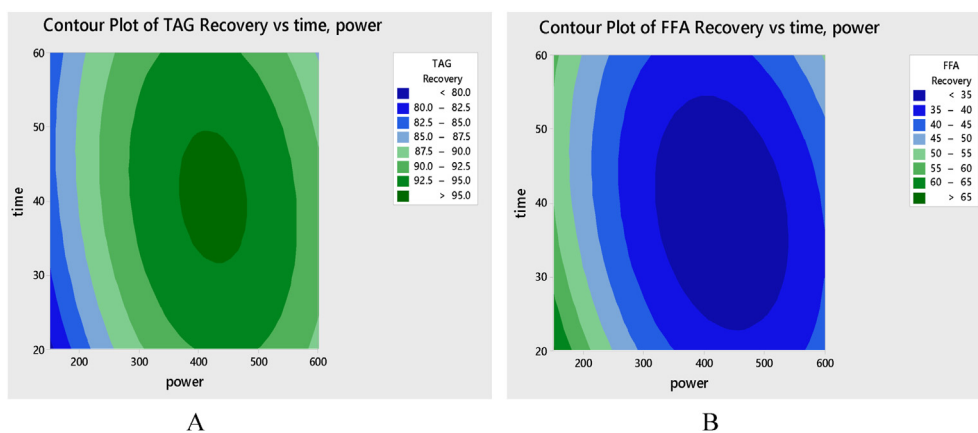


Figure 4. Contour plot on TG recovery (A), FFA recovery (B) based on the RSM method.

Table 5. Rate constant estimation of 1st, 2nd and 3rd order from purification process CGIO at various power.

Power	1st Order		2nd Order		3rd order	
	k	R ²	k	R ²	k	R ²
150	5.7 10 ⁻³	0.5266	5 10 ⁻⁴	0.5163	4 10 ⁻⁵	0.5163
300	5.9 10 ⁻³	0.9391	8 10 ⁻⁴	0.9485	1 10 ⁻⁴	0.9485
450	6.1 10 ⁻³	0.9706	8 10 ⁻⁴	0.9776	1 10 ⁻⁴	0.9776
600	3.2 10 ⁻³	0.9723	4 10 ⁻⁴	0.976	5 10 ⁻⁵	0.976

obtained in the second and third-order reactions. The highest rate constant is in the second-order reactions, so this study's constant kinetics use this model. From the rate constant, the activation energy is obtained by the Arrhenius equation in Eq. (4).

$$k = Ae^{-\frac{Ea}{RT}} \quad (4)$$

where k is rate constant (mol^{-1}); A is collision factor; Ea is activation energy (J/mol); R is gas constant (8.314 J/mol.K), and T is the temperature (K). The Arrhenius equation can be written in its linear form as shown by Eq. (5).

$$\ln k = \ln A - \frac{Ea}{R} \left(\frac{1}{T}\right) \quad (5)$$

To see the correlation between power and temperature, it could be seeing the definition of power. Power is work per time as can be seen in Eq. (6).

$$P = \frac{W}{t} \quad (6)$$

where W is work ($\text{kg m}^2/\text{s}^2$ or J) and t is time (s) so the unit of power or P can be expressed by J/s. As can be seen, work has the same unit as heat (Q). From Eq. (7), it knows that P is directly proportional with temperature (T).

$$Q = m \times cp \times \Delta T \quad (7)$$

where Q is heat (cal or J), m = mass (g or kg), cp = specific heat of the object (cal/g.K or J/kg.K) and ΔT = change in temperature (K). The activation energy (Ea) and the collision factor (A) are obtained from the $1/P$ vs. $\ln k$. The equation is $y = -0.0727x - 0.001$. Previous research has been carried out on the related issue. They found the activation energy from the FFA purification process into TG with conventional methods. The results were 4831.26 J/mol (Nurhidayanti, 2018) while using microwave was 604.43 J/mol. The change of activation energy using the microwave is correlated with entropy increases (Mazubert et al., 2014). The entropy increase is the effect of temperature increase in

an isolated microwave system. The presence of a hydroxyl group (OH) that exposed microwave radiation makes the temperature around the hydroxyl higher than the environment. Required activation energy becomes smaller (Lertsathapornsuk et al., 2008). This method shows more attractiveness, such as a better heating process and yield increase (Gabriel et al., 1998). This heating procedure exerts some force to quickly remove the TG component from the biological matrix (Patil et al., 2011). The activation energy is reduced through the MAE approach. MAE's activation energy of 0.60 kJ/mol produces better transesterification results than s-MWCNTs (45.6 kJ/mol) and KOH catalyst (50.75 kJ/mol). This result indicates that the MAE method is the potential method for biodiesel production.

4. Conclusion

This study refers to biodiesel esterification optimization from crude nyamplung oil. Using RSM (response surface methodology), the optimization results obtained TG purity 90.45% with an operating process at 400 W and 41 min of time extraction. The purity of FFA was obtained as much as 6.6% with an operating process at 436 W and 38 min of time extraction. From the optimal variable, TG recovery is 95.34%, and FFA recovery is 31.45%. Thus, the rate constant value significantly increases at 150, 300, and 450 W and gives the approved result as 0.0005 mol^{-1} , 0.0008 mol^{-1} , and 0.0008 mol^{-1} . However, it drops at 600 W to 0.0004 mol^{-1} . The rate constants have a good value of R^2 , which obtained more than 0.9. The activation energy obtained is less than the conventional method. This result indicates that the MAE method is the potential method for biodiesel production.

Declarations

Author contribution statement

Hakun Wirawastisa Aparamarta: Conceived and designed the experiments; Wrote the paper.

Setiyo Gunawan: Analyzed and interpreted the data; Wrote the paper.

Surya Iryana Ihsanpuro, Doni Satria Buana: Contributed reagents, materials, analysis tools or data.

Imam Safawi: Analyzed and interpreted the data.

Aang Firmansyah Mochtar, M. Yusril Izhar Noer: Performed the experiments.

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Data availability statement

No data was used for the research described in the article.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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