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# Biodiesel synthesis from palm cooking oil utilising sulfuric acid catalyst in a circular microreactor: Optimisation using response surface method

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Abstract. Biodiesel, a renewable and biodegradable fuel, has gained attention as a viable alternative to traditional petroleum-based diesel. Palm oil is an appealing raw material for biodiesel production due to its high oil yield, availability, and favourable fatty acid profile. Microreactor technology has improved the efficiency and control of chemical reactions, especially in biodiesel production. The key challenge is optimising reaction conditions to maximise Fatty Acid Methyl Ester (FAME) content while reducing the kinematic viscosity of the oil. To address this, the Response Surface Methodology (RSM) was employed. The effects of critical input variables such as catalyst loading, reaction temperature, and oil-to-methanol molar ratio on FAME yield and kinematic viscosity were analysed, and the optimal conditions were identified. Transesterification was carried out using a sulfuric acid catalyst in a circular microreactor, with a central composite design examining three input variables and two output variables. Results showed that catalyst loading, reaction temperature, and oil-to-methanol molar ratio significantly increased FAME content and lowered kinematic viscosity. The optimal conditions were determined to be 4.7% catalyst loading, a temperature of 66.8°C, and an oilto-methanol molar ratio of 1:10.

## **1. Introduction**

Growing concerns about environmental pollution and the dwindling supply of fossil fuels have sparked interest in researching sustainable and renewable energy sources. Biodiesel, a renewable and biodegradable fuel, has become a promising substitute for traditional petroleum-based diesel [1]. Biodiesel, produced from vegetable oils, animal fats, and used cooking oils, provides benefits such as lower greenhouse gas emissions, biodegradability, and compatibility with current diesel engines [2-6]. Palm oil is particularly appealing among the various feedstocks due to its high oil content, widespread availability, and beneficial fatty acid composition [7,8].

Conventional biodiesel production entails transesterifying triglycerides using an alcohol and a catalyst, typically an acid, base, or enzyme [9]. The choice of catalyst significantly impacts the reaction rate, yield, and purity of the biodiesel produced [10]. Acid catalysts, like sulfuric acid, are incredibly efficient for processing feedstocks with high free fatty acid content, a common characteristic of palm oil [11]. However, the key challenge is optimising reaction conditions to maximise biodiesel yield, specifically Fatty Acid Methyl Ester (FAME) content and process efficiency, while minimising side reactions and reducing catalyst usage.

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Microreactor technology has opened new avenues for enhancing the efficiency and control of chemical processes [12]. Channel microreactors provide considerable advantages for biodiesel synthesis due to their high surface-area-to-volume ratio and excellent heat and mass transfer characteristics [12]. These reactors enable precise control over reaction conditions, reduced reaction time, and enhanced safety, making them ideal for optimising complex chemical reactions such as biodiesel production [13,14].

This study investigates biodiesel production from palm cooking oil utilising sulfuric acid as a catalyst within a circular microreactor. The reaction parameters are optimised using Response Surface Methodology (RSM). This statistical technique allows for systematically examining the interactions between multiple variables and identifying optimal conditions. RSM not only tools in optimising the FAME content and kinematic viscosity but also provides valuable insights into the significant effect of multiple input variables on multiple output variables.

However, there is still a lack of research on biodiesel synthesis in a circular microreactor using acid catalysts, particularly the significant effect of input variables on output variables. Therefore, this research aims to contribute to developing efficient and sustainable biodiesel production methods, addressing the Sustainable Development Goal (SDG) 7 issue regarding affordable and clean energy. By leveraging the benefits of microreactor technology and advanced optimisation techniques using RSM, this research seeks to advance the field of biodiesel synthesis and pave the way for its broader adoption as a clean and renewable energy source. Additionally, this research seeks to measure the effects of various input variables-catalyst loading, reaction temperature, and the oil-to-methanol molar ratio on the output variables of FAME content and kinematic viscosity.

## 2. Materials and methods

## 2.1 Materials

Palm cooking oil was purchased from a supermarket in Surabaya. Methanol (Merck), sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) 95-97% (Merck), potassium hydroxide (Merck) and magnesium sulphate anhydrous (RPI) were used without further purification.

## 2.2 Experimental setup

The transesterification reaction was run in a circular microreactor with ID 1 mm and length 2 m made from PTFE material. The microreactor was placed in a water bath that could maintain the temperature at a desired level. The palm cooking oil was prepared in the first syringe pump, and methanol with the sulfuric acid catalyst in another syringe pump were injected into the circular microreactor through the T junction. This study utilised two syringe pumps (NEMESYS highpressure syringe pump type NEM-B203-01 B) to maintain a consistent liquid flow throughout the microreactor. These pumps can handle liquids at flow rates ranging from 171.0 nl/min to 825 ml/min, with a maximum pumping pressure of 12 bar for a 100 ml syringe. The two-phase flow pattern was visualised using a High-Speed Digital Camera (CCD HCC-1000) and an SMZ-10 microscope (Nikon), along with image processing software NV 1000 (New Vision Technologies) and a light source (LED lamp). It allows the capture of the slug shape and detects colour changes. The experimental setup is illustrated in Figure 1.



Figure 1. Experimental setup.

## 2.3 Characterisation of palm cooking oil

The fatty acid composition of palm cooking oil was assessed by converting it to FAME through derivatisation with a sulfuric acid catalyst, and the modified procedure is outlined as follows [15]: 25 g oil, 5 ml sulfuric acid catalyst and 100 ml methanol were added into the round-bottom flask. Then, the mixture was refluxed at 65°C for a 10-h reaction time. Next, the refluxed product was neutralised using potassium hydroxide, extracted with water, and separated into organic and water phases. Next, magnesium sulphate was added to the oil phase and filtrated to acquire water-free oil. The oil phase, which contains FAME, was analysed using Gas Chromatography (GC) to assess the fatty acid composition of palm cooking oil.

#### 2.4 Biodiesel synthesis

The first syringe pump was designated for the oil phase containing palm cooking oil, while the second syringe pump was set up with an aqueous phase consisting of a mixture of methanol and sulfuric acid catalyst. The circular microreactor used for the transesterification reaction was placed in a water bath to control the reaction temperature. Each reactant in the syringe was then pumped into the microreactor, and the reaction temperature was maintained as expected, following the experimental design mentioned in Table 3. The methanol and sulfuric acid flow rate mixture was maintained at 0.0334 ml/min. Conversely, the oil flow rate was adjusted within the range of 0.0231 to 0.0658 ml/min to achieve the desired molar ratio of oil to methanol, as outlined in the experimental design presented in Table 3. The oil and methanol flow rates applied at that range result in a stable slug flow pattern with a regular liquid velocity along the channel. Biodiesel synthesis is carried out under a slug flow pattern. The reaction product was collected, neutralised and then cooled. Water was introduced into the separating funnel to extract methanol from the oil phase, and the mixture was decanted to separate the oil phase (FAME) from the water-soluble components. The FAME was subsequently washed with warm water until the wash water reached a neutral pH. Magnesium sulphate anhydrous was added to the FAME oil to separate water from FAME and then filtrated. The FAME product was analysed using gas chromatography, and the FAME content was determined using equation 1 [16]:

$$\%FAME = \frac{\text{area all FAME}}{\text{area of all reference}} x \frac{\text{mass of reference}}{\text{mass of biodiesel sample}}$$
(1)

The kinematic viscosity was measured using the viscometric method.

2.5 Experimental design and optimisation of biodiesel synthesis

A full factorial central composite design (CCD) was employed, and the total number of experiments can be calculated using the equation  $2^n + 2n + n_0$  [17]:

where: n = the number of input variables

- 2<sup>n</sup> = factorial design
- 2n = star point

 $n_0$  = the number of replications at the central value.

The optimisation was conducted for three input variables (catalyst loading, reaction temperature, and oil-to-methanol molar ratio), designated as  $X_1$ ,  $X_2$  and  $X_3$  across five levels (-1.682,-1,0,1,1.682) according to the equation:

$$X_i = \frac{x_i - x_0}{\Delta x_i} \tag{2}$$

Where:  $X_i$  = the coded value of the input variable

 $x_i$  = the actual value of the input variable

 $x_0$  = the actual value of the input variable at the central value

 $\Delta x_i$  = the interval value

The central value  $(n_0)$  for biodiesel synthesis was defined by a catalyst loading of 3%, a temperature of 50°C, and an oil-to-methanol molar ratio of 1:7. The range and levels of the input variables are displayed in Table 1.

Input variables	Coded values	Levels				
		(-1.682)	-1	0	1	1.682
Catalyst loading (%)	<i>X</i> <sub>1</sub>	1.3	2	3	4	4.7
Reaction temperature (°C)	$X_2$	33.2	40	50	60	66.8
Molar ratio oil to methanol	$X_3$	1:3.6	1:5	1:7	1:9	1:10.4

Table 1. The range and levels of variables.

## 2.6 Statistical analysis

The relationship between the experimental data variables (outputs) and the input variables in Table 3, expressed in coded values, was modelled using a second-order polynomial, as shown in Equation 3 [18]:

$$Y_n = \beta_0 + \sum_{i=1}^n \beta_i X_i + \sum_{i=1}^n \sum_{j=1}^{i-1} \beta_{ij} X_i X_j$$
(3)

Where  $Y_n$  is the output variables

 $\beta_i$  and  $\beta_{ij}$  are model coefficients.

For the effect of three input variables on output variables, equation (3) is further explained as:

$$Y_n = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{12} X_{12} + \beta_{13} X_{13} + \beta_{23} X_{23}$$
(4)

Where  $Y_n(n = 1 - 2)$  is the output variables (FAME content and kinematic viscosity);  $\beta_0$  is constant;  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  are the linear coefficients;  $\beta_{11}$ ,  $\beta_{22}$  and  $\beta_{33}$  represent the quadratic

coefficients;  $\beta_{12}$ ,  $\beta_{13}$  and  $\beta_{23}$  are the interaction coefficients. Minitab software was utilised to generate the response surface regression within the Analysis of Variance (ANOVA) package.

## 3. Results and discussions

## 3.1 Palm cooking oil characteristics

The fatty acid composition of palm cooking oil was analysed using the derivatisation method. Triglycerides in the oil were reacted with methanol to produce methyl ester using an acid catalyst, allowing a complete reaction. The Fatty Acid Methyl Ester (FAME) products were subsequently analysed using Gas Chromatography (GC), and the resulting FAME composition was converted into fatty acid composition. Table 2 displays the fatty acid composition of palm cooking oil determined through the derivatisation method.

Fatty acid	Composition (%)
Lauric acid	0.65
Miristic acid	1.35
Palmitic acid	38.27
Oleic acid	41.04

18.69

**Table 2**. Composition of fatty acids in palm cooking oil.

## 3.2 Statistical analysis of response surface method

Linoleic acid

A total of 20 experiments were carried out for all specified points according to the variable ranges and levels outlined in Table 1, along with the experimental design presented in Table 3. The experimental points design was conducted in a randomised order, and the results for the two output variables (FAME content and kinematic viscosity) are also shown in Table 3.

Exp	Catalyst loading	Reaction	Molar ratio	FAME content	Kinematic
No	(%)	Temperature (°C)	oil to methanol	(%)	viscosity (cSt)
	$X_1$	$X_2$	X3	$Y_1$	Y2
1	1 (4)	1 (60)	-1 (1:5)	55.78	15.17
2	1 (4)	-1 (40)	1 (1:9)	40.94	20.58
3	0 (3)	0 (50)	0 (1:7)	40.58	20.91
4	-1 (2)	1 (60)	1 (1:9)	42.78	18.85
5	0 (3)	0 (50)	0 (1:7)	41.35	20.16
6	-1 (2)	-1 (40)	-1 (1:5)	11.64	29.78
7	0 (3)	0 (50)	0 (1:7)	42.04	19.43
8	1.682 (4.7)	0 (50)	0 (1:7)	58.41	14.90
9	0 (3)	0 (50)	0 (1:7)	40.37	19.73
10	0 (3)	0 (50)	0 (1:7)	41.95	19.07
11	0 (3)	0 (50)	-1.682 (1:3.6)	28.46	24.22
12	1 (4)	-1 (40)	-1 (1:5)	33.51	22.84
13	0 (3)	1.682 (66.8)	0 (1:7)	49.05	17.81
14	-1 (2)	-1 (40)	1 (1:9)	23.22	25.95
15	-1.682 (1.3)	0 (50)	0 (1:7)	15.93	28.77
16	0 (3)	-1.682 (33.2)	0 (1:7)	20.96	25.68
17	-1 (2)	1 (60)	-1 (1:5)	29.98	23.72

**Table 3.** The Experimental design and output variables.

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Exp	Catalyst loading	Reaction	Molar ratio	FAME content	Kinematic
No	(%)	Temperature (°C)	oil to methanol	(%)	viscosity (cSt)
	$X_1$	$X_2$	X3	$Y_1$	$Y_2$
18	1 (4)	1 (60)	1 (1:9)	64.41	12.21
19	0 (3)	0 (50)	1.682 (1:10.4)	46.37	18.29
20	0 (3)	0 (50)	0 (1:7)	45.89	18.45

The FAME content ( $Y_1$ ) and kinematic viscosity ( $Y_2$ ) were measured during the transesterification reaction in the microreactor to establish their correlation with the respective input variables: catalyst loading ( $X_1$ ), reaction temperature ( $X_2$ ) and oil-to-methanol molar ratio ( $X_3$ ). Response surface regression was conducted using Minitab software to assess the relationship between the output variables  $Y_1$  and  $Y_2$  and the input variables ( $X_1$ ,  $X_2$ ,  $X_3$ ). Table 4 represents the obtained regression statistics, whereas Table 5 provides the analysis of variance (ANOVA). The data correlation value ( $R^2$ ) of 0.985 for FAME content and 0.969 for kinematic viscosity demonstrated a strong fit for the model in illustrating the relationship between the input and output variables.

 Table 4. Regression statistics for FAME content and kinematic viscosity.

Regression statistics	FAME content $(Y_1)$	Kinematic viscosity $(Y_2)$
R <sup>2</sup>	0.985	0.969
Adjusted R <sup>2</sup>	0.972	0.941
Predicted R <sup>2</sup>	0.923	0.823
Standard error	2.310	1.099

Parameters	FAME content ( <i>Y</i> <sup>1</sup> )	Kinematic viscosity (Y <sub>2</sub> )
DF	9	9
Adjusted SS	3575.13	378.145
Adjusted MS	397.24	42.016
F-value	74.47	34.81
P-value	0.000	0.000

**Table 5.** Analysis of Variance (ANOVA) for the model.

**Table 6.** Significance of regression coefficients for FAME content (*Y*<sub>1</sub>).

	Coefficients	Standard error	T-value	P-value
Constant	41.979	0.942	44.57	< 0.001
$X_1$	9.584	0.625	15.33	<0.001 <sup>a</sup>
X2	11.603	0.625	18.57	<0.001 <sup>a</sup>
X3	5.167	0.625	8.27	<0.001 <sup>a</sup>
X1 <sup>2</sup>	-2.149	0.608	-3.53	$0.005^{b}$
X2 <sup>2</sup>	-1.384	0.608	-2.27	0.046 <sup>c</sup>
X3 <sup>2</sup>	-1.297	0.608	-2.13	0.059
$X_1X_2$	0.980	0.817	1.20	0.258
$X_1X_3$	0.303	0.817	0.37	0.719
$X_2X_3$	-1.040	0.817	-1.27	0.232

<sup>a</sup> significant at 0.1% (p<0.001)

<sup>b</sup> significant at 1.0% (p<0.01)

<sup>c</sup> significant at 0.5% (p<0.05)

IOP Conf. Series: Earth and	Environmental Science	<b>1445</b> (2025) 012061
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	Coefficients	Standard error	T-value	P-value
Constant	19.644	0.448	43.84	< 0.001
$X_1$	-3.107	0.297	-10.45	<0.001 <sup>a</sup>
X2	-3.722	0.297	-12.52	<0.001 <sup>a</sup>
X3	-1.750	0.297	-5.89	<0.001 <sup>a</sup>
$X_1^2$	0.624	0.289	2.16	0.056
$X_2^2$	0.656	0.289	2.27	0.047°
X <sub>3</sub> <sup>2</sup>	0.451	0.289	1.56	0.150
$X_1X_2$	-0.360	0.388	-0.93	0.376
$X_1X_3$	-0.217	0.388	-0.56	0.588
$X_2X_3$	0.435	0.388	1.12	0.289

Table 7. Significance of regression coefficients for kinematic viscosity ( )	$Y_2$	2	)	).	•	•
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<sup>a</sup> significant at 0.1% (p<0.001)

 $^{\rm b}$  significant at 1.0% (p<0.01)

 $^{\rm c}$  significant at 0.5% (p<0.05)

The elevated correlation values (R<sup>2</sup>) for the data outputs indicated a strong alignment between the model and the experimental data. Minitab software was employed to analyse the data and visualise the results using surface plots.

#### 3.3 Influence of catalyst loading, temperature, and molar ratio on FAME content

A second-order polynomial model was fitted to the CCD experimental data using response surface regression in Minitab software. The effect of three input variables (catalyst loading, temperature and molar ratio on FAME content (%) in coded values utilising the response surface method is represented by equation 5 below:

$$Y_{1} = 41.979 + 9.584X_{1} + 11.603X_{2} + 5.167X_{3} - 2.149X_{1}^{2} - 1.384X_{2}^{2} - 1.297X_{3}^{2} + 0.980X_{1}X_{2} + 0.303X_{1}X_{3} - 1.040X_{2}X_{3}$$
(5)

 $Y_1$  (FAME content in %) is the output variable, and  $X_1$ ,  $X_2$  and  $X_3$  are the input variables (catalyst loading, temperature and molar ratio) in coded values. Figure 2 illustrates the interaction effects of the input variables on the output FAME content. Each plot demonstrates how the interaction of input variables affects the increase in FAME content as the output while keeping the other variables at their central values. Figure 2A illustrates the impact of both catalyst loading and reaction temperature. At a 1:7 molar ratio of oil to methanol, the FAME content of the oil increases more rapidly with rising reaction temperature than with increased catalyst loading. Figure 2B shows a similar effect of catalyst loading and the molar ratio of oil to methanol on the increasing FAME content achieved at a reaction temperature of 50°C, with catalyst loading having a more significant impact than the molar ratio. Figure 2C illustrates the combined effect of reaction temperature and the molar ratio of oil to methanol (at 3% catalyst loading) on FAME content. Both input variables similarly affect the increasing amount of FAME in biodiesel.

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Figure 2. Interactive effect of input variables on FAME content.

Overall, the results demonstrate that the FAME content in biodiesel significantly increases linearly with higher catalyst loading, reaction temperature, and molar ratio of oil to methanol, showing statistical significance at p<0.001 (Table 6). The most significant effect of input variables on FAME content is reaction temperature. These input variables (catalyst loading, reaction temperature, and molar ratio) positively impact FAME content. Triglycerides made of fatty acids are transformed into methyl esters in the microreactor via the transesterification reaction, as evidenced by the increasing amount of FAME [19]. There are three steps for the conversion of triglyceride to FAME; follow the reaction mechanism below [20]:

 $TGC + Me \leftrightarrow DGC + ME$  $DGC + Me \leftrightarrow MGC + ME$  $MGC + Me \leftrightarrow GLC + ME$ 

where: TGC = Triglyceride; Me = Methanol; DGC = Diglyceride; MGC = Monoglyceride; GLC = Glycerol; ME = Methyl Ester

Figure 3 presents the chromatogram of the FAME profiles obtained from this study.



*3.4 Influence of catalyst loading, temperature and molar ratio on kinematic viscosity* The correlation equation that relates kinematic viscosity to the three input variables (catalyst loading, reaction temperature, and molar ratio of oil to methanol) in coded units is shown below:

$$Y_{2} = 19.644 - 3.107X_{1} - 3.722X_{2} - 1.750X_{3} + 0.624X_{1}^{2} + 0.656X_{2}^{2} + 0.451X_{3}^{2} - 0.360X_{1}X_{2} - 0.217X_{1}X_{3} + 0.435X_{2}X_{3}$$
(6)

The results indicate that the kinematic viscosity of biodiesel is a quadratic function of reaction temperature (significant at p<0.05) and a linear function of both catalyst loading and the molar ratio of oil to methanol (significant at p<0.001), as shown in Table 7.

Figure 4 illustrates the interaction effects of the input variables on kinematic viscosity. Specifically, Figure 4A depicts the combined effects of catalyst loading and reaction temperature on kinematic viscosity. The plot indicates that both catalyst loading and reaction temperature significantly influence the reduction of biodiesel kinematic viscosity. The interaction between catalyst loading and the molar ratio of oil to methanol is presented in Figure 4B. It is also observed that kinematic viscosity decreases significantly when both factors are increased. Figure 4C illustrates how the interaction between the reaction temperature and the oil-to-methanol molar ratio influences the kinematic viscosity. The results demonstrated that increasing both the reaction temperature and the molar ratio of oil to methanol led to a substantial decrease in kinematic viscosity. It was observed that higher levels of catalyst loading, reaction temperature, and molar ratio of oil to methanol negatively impacted the output variable, resulting in a reduction in kinematic viscosity.





Figure 4. Interactive effect of input variables on kinematic viscosity.

Kinematic viscosity is one of the critical factors for biodiesel properties in determining the quality and performance of biodiesel as a fuel. The aim of transforming palm oil into FAME is to lower the kinematic viscosity of the original oil, producing biodiesel that can be used in diesel engines [21]. The experimental results in Table 3 show that the obtained biodiesel does not satisfy the kinematic viscosity standard for biodiesel in Indonesia, which should be in the range of 2.3 - 6.0 cSt [22]. Higher FAME content will result in lower kinematic viscosity of biodiesel. The residence time of reactants needs to increase by utilising a longer microreactor.

The optimum condition was achieved using a response optimiser in Minitab and obtained by maximising the FAME content point and minimising the kinematic viscosity point. The optimal conditions were identified with a catalyst loading of 1.682, a reaction temperature of 1.682, and a molar ratio 1.512, represented as coded values. The actual values of the input variables at the optimal conditions for the range variables in this study were derived by converting the coded values to actual values using Equation 2, resulting in a catalyst loading of 4.7%, a reaction temperature of 66.8 °C, and a molar ratio of oil to methanol of 1:10.0.

#### 4. Conclusion

The optimisation of biodiesel production using a microchannel reactor was conducted through the response surface method, focusing on the impact of three variables: catalyst loading, reaction temperature, and the molar ratio of oil to methanol. The response surface method is a very efficient way to optimise as it reduces the number of experiments, saves time, and is highly efficient. The findings indicated that higher catalyst loading, longer reaction temperature, and a higher molar ratio of oil to methanol led to increased FAME content and a detrimental decrease in the kinematic viscosity of the biodiesel. These three input variables significantly affect the obtained FAME and kinematic viscosity value. The optimal conditions for biodiesel synthesis using a circular microreactor were achieved with a catalyst loading of 4.7%, a temperature of 66.8 °C, and a molar ratio of oil to methanol of 1:10.0.

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#### References

- [1] Mohd Noor C W, Noor M M and Mamat R 2018 Renewable and Sustainable Energy Reviews 94 127
- [2] Issariyakul T and Dalai A K 2014 Renewable and Sustainable Energy Reviews 31 446
- [3] Toldrá-Reig F, Mora L and Toldrá F 2020 Applied Sciences 10 10
- [4] Hanaki K and Portugal-Pereira J 2018 'The Effect of Biofuel Production on Greenhouse Gas Emission Reductions', in *Biofuels and Sustainability: Holistic Perspectives for Policy-making*, Takeuchi K, Shiroyama H, Saito O and Matsuura M, Eds., (Tokyo: Springer Japan)
- [5] Tamalampudi S and Fukuda H 2011 3.07 Biodiesel in *Comprehensive Biotechnology (Second Edition)*, M. Moo-Young, Ed., (Burlington: Academic Press)
- [6] Nguyen V G, Pham M T, Le N V L, Le H C, Truong T H and Cao D N 2023 International Journal of Renewable Energy Development **12** 4
- [7] Elgharbawy A S, Sadik W A, Sadek O M and Kasaby M A 2021 Journal of the Chilean Chemical Society 66 5098
- [8] Zahan K A and Kano M 2018 *Energies* **11** 8
- [9] Farouk S M, Tayeb A M, Abdel-Hamid S M S and Osman R M Environmental Science and Pollution Research 31 9
- [10] Atadashi I M, Aroua M K, Abdul Aziz A R and Sulaiman N M N 2013 Journal of Industrial and Engineering Chemistry **19** 1
- [11] Nurulain S, Aziz N, Najib M S, Salim M R and Manap H Journal of Physics: Conference Series 1921 012055
- [12] Bastan F and Kazemeini M 2022 Journal of Particle Science and Technology 8 2
- [13] Suryawanshi P L, Gumfekar S P, Bhanvase B A, Sonawane S H and Pimplapure M S 2018 *Chemical Engineering Science* **189** 431
- [14] Zhang Y 2018 IOP Conference Series: Earth and Environmental Science 113 1
- [15] Pontoh J and Buyung N T N 2011 Jurnal Ilmiah Sains 11 2
- [16] Rahimi M, Aghel B, Alitabar M, Sepahvand A and Ghasempour H R 2014 Energy Conversion and Management 79 599
- [17] Sadhukhan B, Mondal N K and Chattoraj S 2016 Karbala International Journal of Modern Science 2 3
- [18] Tran N N, McMurchie E J and Ngothai Y 2018 *Chemistry Select* **3** 9
- [19] Anisah P M, Suwandi and Agustian E 2019 Journal of Physics: Conference Series 1170 1
- [20] Shahbazi M R, Khoshandam B, Nasiri M and Ghazvini M 2012 Journal of the Taiwan Institute of Chemical Engineers 43 4
- [21] Gorey N, Ghosh S, Srivastava P and Kumar V 2017 *IOP Conference Series: Materials Science and Engineering* **225** 1
- [22] Salawali R T, Ibrahim M and Lestari M F 2023 SATERA: Jurnal Sains dan Teknik Terapan 1 1