

Article

Optimization of Biodiesel Production from Waste Cooking Oil in a Continuous Mesoscale Oscillatory Baffled Reactor

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Abstract. In this study, a mesoscale oscillatory baffled reactor (OBR) was used to synthesize high methyl esters from waste cooking oil (WCO) in an alcoholic hydroxide solution. Preliminary experiments were conducted to screen for appropriate oscillating frequency and reaction temperature for the transesterification of WCO. Response surface methodology (RSM) based on the Box-Behnken design (BBD) was employed to investigate the influence of residence time, amount of catalyst and methanol-to-oil molar ratio on the fatty acid methyl ester (FAME) content of the product obtained from the OBR. Based on the response surface approach, the optimum operating conditions for this process were as: a residence time of 60 s, a catalyst content of 3.0%, and a methanol-to-oil molar ratio of 11. The physical and chemical properties of the product obtained were found to meet the standards.

Keywords: Waste cooking oil; biodiesel; transesterification; oscillatory baffled reactor.

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1. Introduction

The limit of petroleum reserves has drawn attention to explore alternative sources as well as to develop novel technologies for the production of alternative fuels from relatively abundant and inexpensive resources. One of the most versatile and promising options is the transformation of triglyceride content in vegetable oil to fatty acid methyl esters (FAME) or biodiesel and glycerol through the transesterification reaction. There are currently three main groups of vegetable oils available for biodiesel production, including edible oils, inedible oils and waste cooking oils. Although edible oils can produce high quality biodiesel, they are not a reliable source of feedstock because of their high price and the competition with the food-processing industries. On the other hand, inedible oils are difficult to harvest with very low oil yields per hectare of plantation area [1,2]. Recently, utilization of waste cooking oils (WCO) as feedstock for biodiesel production has gained more attention, because WCO is relatively inexpensive and available all year round. Furthermore, the use of WCO as feedstock for the biodiesel production can also reduce the amount of WCO that is recycled for human consumption [3].

The production of biodiesel from WCO is currently a challenging process because it contains a high concentration of free fatty acid (FFA), which can react with triglyceride through the saponification reaction to form undesirable soap, causing a reduction in FAME content. To overcome this problem, a two-step process has been developed for biodiesel production from high FFA-containing oil. For the first step, the acid-catalyzed esterification reaction of a high FFA feedstock is performed to reduce the FFA content. For the second step, the product from the first step is further processed by the transesterification reaction. Several studies have shown that the esterification reaction requires a high molar ratio of alcohol to oil and can be carried out over either a homogeneous or heterogeneous acid catalyst [4-6]. The transesterification reaction of WCO in a batch reactor with conventional heating and mechanical stirring can achieve up to 95% of FAME under the optimum conditions of a 12:1 methanol-to-oil molar ratio, 60°C, and a reaction time of 120 min in the presence of 1 wt% NaOH [7]. A replacement of conventional heating with microwave heating was found to increase the rate of transesterification reaction by at least 10 fold [8, 9]. Lee et al. [10] reported a production of biodiesel with 96-98% FAME from a low acid value WCO at a 6 min reaction time in a batch reactor with mechanical stirring, 500 W microwave heating and 1.0 wt% KOH. An increase in the FFA content in a feedstock was found to need increases in both the microwave power to 600W and an amount of catalyst to 1.2 wt%. Another process, known as simultaneous cooling and microwave heating was reported to achieve 75% efficiency for biodiesel production using a microalgae feedstock, which is 5-7 times better than those processes using conventional heating and normal microwave heating. However, in order to conserve energy when using microwave, it is important for the reaction

medium to be moisture-free [11]. Although utilization of microwave irradiation can reduce reaction time significantly, from the engine performance testing results, the brake power generated from microwave-assisted biodiesel product is lower than that from biodiesel produced conventionally [12].

Apart from a selection of an appropriate feedstock and operating conditions, the type of reactor to be used for transesterification reaction is also an important point. The reactor must be able to produce biodiesel with a high FAME content of at least 96.5% according to the EN 14214 standard, while also facilitating low-cost production and low energy consumption. Recently, several process intensification techniques including microwave-assisted transesterification, ultrasonic cavitation and hydrodynamic cavitation have been employed successfully for biodiesel production [13, 14]. Several researches reported that a reduction in transesterification reaction time was achieved after ultrasonic wave was used [15]. Furthermore, Nayebzadeh et al. reported that the biodiesel produced from the ultrasonic-assisted process had relatively low viscosity and a higher oxygen content, resulting in superior combustion performance [16]. Additionally, the combined microwave and ultrasonic methods were employed for lipid extraction but organic matter may be degraded if it is exposed to high irradiation [17]. Oscillatory flow in baffled tubes is a novel technology that has received increasing attention in recent years. It offers several advantages in chemical engineering processes over conventional reactors such as uniform mixing, including higher mass and heat transfer, compact reactor design and linear scale-up [18].

The oscillatory baffled reactor (OBR) consists of a series of columns and each column has a specific number of baffles and an oscillation motion creator, which is generally either a piston or bellows connected with a motor. It is well known that OBR technology offers the combined benefits of continuous production from tubular reactors and effective mixing in stirred batch reactors. On the other hand, an OBR can provide a higher degree of mixing with plug flow pattern even at a low net flow rate. The mixing intensity in the OBR is independent of the net flow and controlled by the oscillation conditions [18,19]. The flow pattern with a very high degree of mixing is created by having baffles and the oscillatory motion. The movement of liquid within the baffled restriction space causes uniform formation of vortices equivalent to small agitation spots, which greatly enhances both the mass and heat transfer inside the reactor [20]. The fluid mechanical condition in an OBR can be regulated through frequency and amplitude of the oscillatory motion, as expressed numerically by the oscillatory Reynolds number (Re_o) and the Strouhal number (St). The Re_o gives an indication of mixing intensity inside the reactor. Plug flow characteristics can be achieved within each baffle cavity in the range of Re_o of 50-500 [19]. The St value is a measure of the vortex propagation. Large St values tend to give poor vortex formation and to cause mixing in the axial direction. According to the literature, the proper range for

St is 0.01-9 [18]. In addition, the intensity of mixing in the OBR is decoupled from the net flowrate if the ratio of the Re_o to the net flow Reynolds number is in the range of 2-6 [19]. Therefore, long residence time processes in reduced length reactors can be achieved while a high degree of mixing intensity is maintained. Furthermore, it was demonstrated through residence time distribution (RTD) experiments that an OBR had a mixing intensity equivalent to more than 50 stirred tanks put together in series [6]. Phan et al. [21] reported that 97% FAME biodiesel was successfully produced through the transesterification of rubber seed oil (RSO) in an OBR at 60°C, a 6:1 methanol-to-oil ratio, and a 1.5wt% KOH loading. Additionally, it was demonstrated that sharp-edged helical baffles gave better mixing quality than normal helical baffles due to the increased shear force by the sharp edges. Apart from the transesterification reaction, an OBR has other potential applications including polymerization [22, 23], ozone-water mass transfer [24], esterification [6] and enzymatic scarification [25]. Nevertheless, few research studies have been conducted to investigate the synthesis of biodiesel from WCO using OBR.

Herein, the main objective of this study was to enhance the transesterification of WCO using a mesoscale OBR. Three reaction parameters of alcohol-to-oil molar ratio, residence time, and amount of catalyst were optimized by using the Response Surface Methodology (RSM) with the Box-Behnken design to minimize the number of experiments. The resultant products were purified and characterized to determine fatty acid methyl esters (FAME) content, acid value, iodine value, and viscosity. The results of the current study will be useful for industrial-scale production of biodiesel from WCO.

2. Experimental

2.1. Materials

Waste cooking oil (WCO) collected from leftover frying palm oils which was supported from Thanachock Vegetable Oil LTD., PART in Thailand was used as feedstock. The basic chemical and physical properties of the studied WCO is shown in Table 1. Sulfuric acid (98wt%) and potassium hydroxide (85wt%) obtained from Ajax Finechem Pty were used as catalysts for the esterification and transesterification reactions, respectively. Commercial grade methanol (99.5wt%) was obtained from Quality Reagent Chemical.

2.2. Biodiesel Production Experiment

The OBR used in this study had a liquid holding volume of 300 mL and was made of a glass tube 448.5 cm in length and 11.0 mm in internal diameter. The tube had baffles inside and each baffle had an inner hole 6.0 mm in diameter with spacing between baffles of 14.5 mm. The oscillatory motion of the fluid inside the reactor was regulated by a variable-stroke piston pump. The oscillation amplitude was able to be adjusted from 0 to 30 mm. However, in this experiment, the oscillation amplitude was fixed at 8.0 mm ($St = 0.1$). The oscillation frequency was

adjusted from 0 to 8.0 Hz by varying the rotation speed of a 40 W DC motor.

Table 1. Physical and chemical properties of WCO.

Properties	Units	WCO
Acid value	mg KOH/g	4.14
Density	kg/m ³	910.1
Kinematic viscosity at 40°C	mm ² /s	42.5
Water content	mg/kg	848.1
Gross calorific value	MJ/kg	36.5
Elemental analysis		
% C	% w/w	69.10
% H	% w/w	11.19
% N	% w/w	0.27

Prior to the transesterification step, WCO was filtered to remove all suspended solids. The basic physical and chemical properties of the filtered WCO are shown in Table 1. It was pretreated via the esterification reaction, in which WCO was reacted with methanol using 6.0 wt% H₂SO₄ as a catalyst at 65°C, a methanol-to-oil molar ratio of 24:1, a residence time of 12 min and an oscillatory frequency of 3.75 Hz with 8.0 mm amplitude. With these reaction conditions, the amount of FFA in WCO was reduced from 2.07 to 0.41 wt%. The esterified oil obtained from this pretreatment step was further used for the transesterification experiments. The two sequential steps of esterification and transesterification are shown in Fig. 1.



Fig. 1. Studied route for biodiesel production from WCO in OBR system.

The transesterification step was also conducted in the same OBR submerged in a temperature controllable water bath (Mermerth, WMB 14). The first set of experiments was preliminarily conducted to obtain the optimum conditions (a reaction temperature and an oscillating frequency). For the second set of experiments, the reactions between the esterified oil and methanol were carried out at 65°C using KOH as a catalyst. The effects of three process parameters of methanol-to-oil molar ratio (9:1, 11:1 and 15:1), amount of catalyst (2.5, 3.0, and 3.5 wt%), and residence time (40, 50, and 60 s), were investigated in this study. The experimental setup of the studied OBR system is shown in Fig. 2.

After the transesterification step, the fraction of crude biodiesel produced was separated from glycerol by gravitational sedimentation and washed with warm deionized water several times to remove impurities. The biodiesel produced was analysed for fatty acid methyl esters content (FAME, %) according to the EN14103 standard [26]. A 50 mg sample of the biodiesel produced

was mixed with 1 mL of a solvent solution containing 10 mg of methyl-heptadecanoate in 1 mL of heptane. The quantity of methyl esters was measured by a gas chromatograph (GC) equipped with a flame ionization

detector (FID) and a Stabilwax column (30 m × 0.25 mm, 0.25 μm).

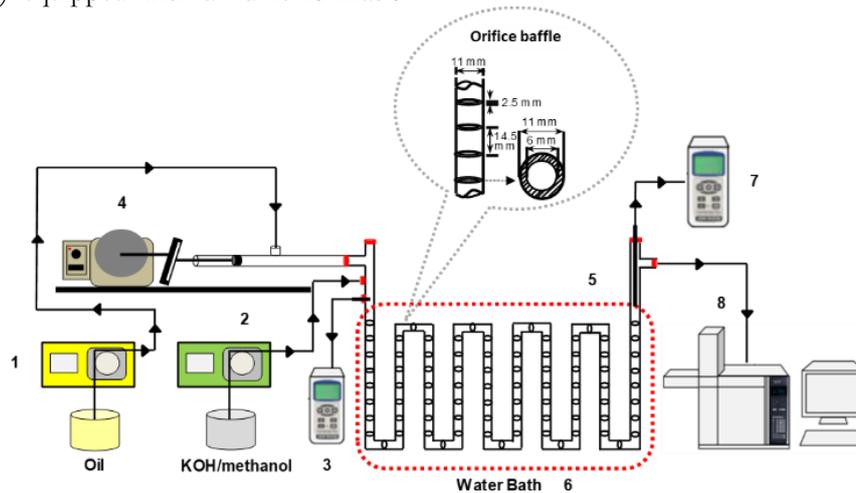


Fig. 2. Schematic diagram of transesterification system for waste cooking oil: (1), (2) Longer pumps (3), (7) Data loggers (4) Oscillator (5) Oscillatory baffled reactor (6) Water bath (8) Gas Chromatography.

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Furthermore, a large amount of biodiesel was produced under the optimum reaction conditions obtained from the response surface methodology (RSM) experiments. The properties of the biodiesel produced analyzed according to the ASTM standard testing procedures were density at 15°C (ASTM D1298), acid value (ASTM D664) using KOH as a titrant by an auto titrator (G20 compact titrator), viscosity at 40°C by a Cannon-Fenske viscometer (ASTM D445), gross calorific value (ASTM D4891) by a bomb calorimeter (IKA C6000), water content (ASTM D2709) using an auto-compact water determinator (C10S Compact KF Coulometer), cloud point and pour point (ASTM D97) using an automatic petroleum tester (TANAKA MPC-102S) and %CHNO contents by a CHNS/O elemental analyzer (Leco 628 series).

2.3. Box-Behnken Experimental Design

The response in terms of FAME content (%) in the products from the transesterification step, as a function of methanol-to-oil molar ratio, amount of catalyst (%), and residence time (s), were also simulated using the Box-Behnken technique. The use of the response surface

methodology (RSM) obviously shows the relationship among process parameters and can provide the optimum transesterification conditions for the production of biodiesel to meet the standard requirement (FAME content > 96.5%). One of the beneficial features of the Box-Behnken design is to require fewer design points; hence it is less expensive and less time-consuming in conducting the experiments. Three process parameters of residence time (X_1), amount of catalyst (X_2), and methanol-to-oil mass ratio (X_3) were varied with 15 experimental runs to determine all process coefficients by fitting the experimental data to the following quadratic equation.

$$Y = \beta_0 + \sum_{i=1}^3 \beta_i X_i + \sum_{i=1}^3 \beta_{ii} X_i^2 + \sum_{i=1}^2 \sum_{j=i+1}^3 \beta_{ij} X_i X_j \quad (1)$$

where Y is the predicted response (FAME%); $\beta_0, \beta_i, \beta_{ii}$ and β_{ij} are the regression coefficients, representing the intercept constants, linear, quadratic, and interaction terms, respectively.

3. Results and Discussion

3.1. Effects of Oscillation Frequency and Reaction Temperature on FAME content

The transesterification reaction is affected by several process parameters including type of reactor, temperature, mixing intensity, pressure, amount of catalyst, type of catalyst, methanol-to-oil molar ratio and residence time. In this research, preliminary experiments were conducted to optimize the transesterification reaction step in order to achieve the acceptable performance (FAME content > 96.5% in produced biodiesel) by using the optimization procedure (Box-Behnken experimental design). The

intensity of mixing was controlled by (3.5, 4.5, 5.5 and 6.5 Hz, corresponding to Re_o values in the range of 100-200) while the other parameters were kept constant at a methanol-to-oil molar ratio of 9, a reaction temperature of 333 K, a residence time of 60 s and an amount of catalyst of 2.5 wt%. As shown in Fig. 3, the FAME content reaches a maximum level of 98% at the frequency of 4.5 Hz, corresponding to the calculated oscillatory Reynolds number of 137 which was in the suggested range [21]. The optimum frequency of 4.5 Hz was selected for the next study of the effect of reaction temperature.

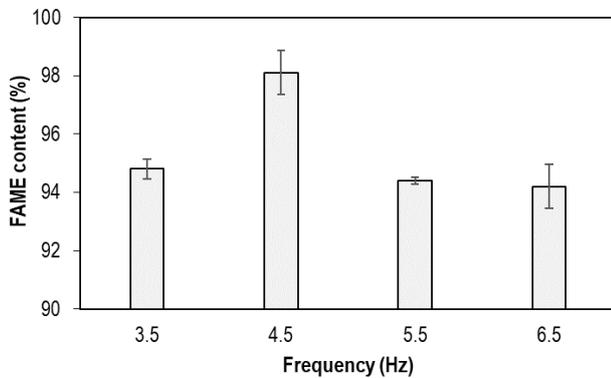


Fig. 3. Effect of oscillating frequency on FAME content. Transesterification conditions: reaction temperature = 333 K, methanol-to-oil molar ratio = 9:1, KOH content = 2.5 wt%, and residence time = 60 s.

The effect of reaction temperature on FAME content was investigated by varying the reaction temperature from 325 to 333 K while the other process

parameters were fixed at a frequency of 4.5 Hz, a methanol-to-oil molar ratio of 9:1, an amount of catalyst (KOH) of 2.5 wt% and a residence time of 60 s. As shown in Fig. 4, the FAME content increases almost linearly with increasing reaction temperature and reaches a maximum level of 98.1% at 333 K. Beyond the optimum reaction temperature of 333 K, the FAME content declined significantly with further increasing reaction temperature from 333 to 338 K. The results were in good agreement with previous investigations that an increase in reaction temperature beyond the boiling point of alcohol caused the reduction in FAME content [13, 27]. This is because at a higher temperature, more methanol becomes gaseous phase with the reduction of methanol concentration in the liquid phase effectively, causing the methanol-to-oil ratio to be too low.

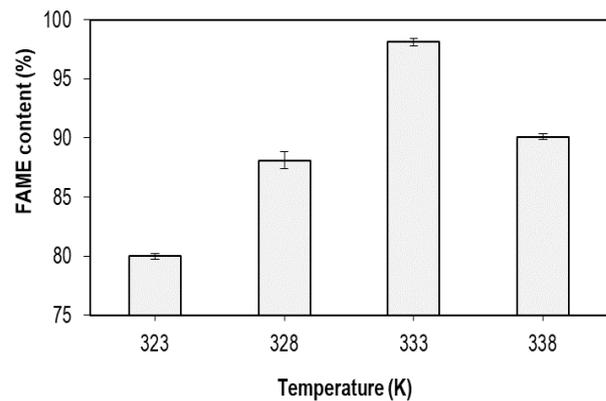


Fig. 4. Effect of reaction temperature on FAME content. Transesterification conditions: frequency = 4.5 Hz, methanol-to-oil molar ratio = 9:1, KOH content 2.5 wt% and residence time = 60 s.

Table 2. Design matrix for the Box-Behnken experiments and the response values of both experimental and predicted FAME contents (%)

Run	Reaction parameters			FAME content (%)	
	X_1 Residence time (s)	X_2 Amount of catalyst (wt%)	X_3 Methanol/oil molar ratio	Experimental	Predicted
1	40	2.5	12	85.9±0.5	87.0
2	40	3.0	9	84.7±0.4	83.6
3	40	3.0	15	93.8±1.7	93.1
4	40	3.5	12	84.4±0.5	85.1
5	50	2.5	9	83.7±0.5	83.6
6	50	2.5	15	86.4±0.3	86.0
7	50	3.0	12	94.3±0.7	94.3
8	50	3.0	12	94.3±0.6	94.3
9	50	3.0	12	94.3±0.7	94.3
10	50	3.5	9	83.0±0.4	83.4
11	50	3.5	15	86.4±1.9	86.5
12	60	2.5	12	94.1±1.6	93.4
13	60	3.0	9	98.1±1.3	98.8
14	60	3.0	15	93.8±2.0	94.9
15	60	3.5	12	96.8±1.9	95.7

Table 3. ANOVA for response surface model (Eq. (2)) of transesterification reaction.

	Degree of freedom	Sum of squares			Mean square			F-value	Significance F
Model	9	395.67			43.96			30.78	0.00075
Residual	5	7.143			1.429				
P-value	X_1	X_2	X_3	X_1X_2	X_2X_3	X_1X_3	X_1^2	X_2^2	X_3^2
	0.38118	0.00060	0.00114	0.13926	0.78141	0.00250	0.03029	0.00023	0.00227

Table 4. ANOVA for response surface model (Eq. (3)) of transesterification reaction.

	Degree of freedom	Sum of squares			Mean square			F-value	Significance F
Model	7	391.14			55.88			33.50	0.00007
Residual	7	11.675			1.668				
P-value	X_1	X_2	X_3	X_1X_3	X_1^2	X_2^2	X_3^2		
	0.89630	0.00005	0.00015	0.00127	0.02764	0.00005	0.00112		

3.2. Optimization of FAME content from Transesterification Reaction

The results from the Box-Behnken experiments (with the input data from the 15 runs) were employed to optimize the transesterification reaction. The design matrix and the resulting FAME contents evaluated from the three independent variables of residence time, amount of catalyst and methanol-to-oil molar ratio are shown in Table 2. By using the regression analysis on these experimental results, the relationship between the response variables and the coefficients was formulated mathematically in the following quadratic equation (Eq. (2)):

$$\begin{aligned}
 \text{FAME} (\%) = & -185.57 - 0.7275X_1 + 128.92X_2 \\
 & + 15.18X_3 + 0.2100X_1X_2 \\
 & + 0.1117X_2X_3 - 0.1117X_1X_3 \quad (2) \\
 & + 0.0185X_1^2 - 23.45X_2^2 \\
 & - 0.3958X_3^2
 \end{aligned}$$

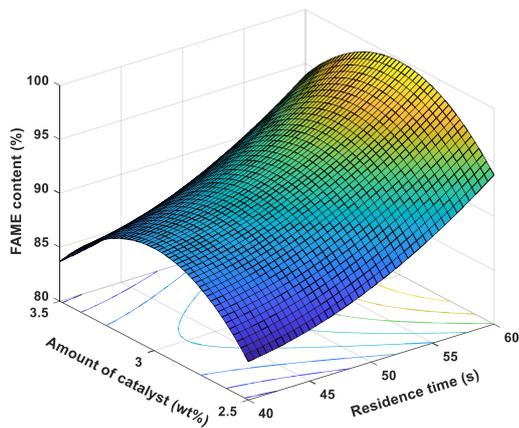
The ANOVA results are shown in Table 3. The F-value (30.78) which is higher than $F_{(0.05,9,5)}$ (4.773) and significance F (0.00075) of the analysis shows an excellent fit of this model. Additionally, the P-values of the linear coefficients for both residence time and methanol-to-oil molar ratio parameters were lower than 0.05, indicating that these operating conditions have a significant effect on the FAME content. However, the P-value of the amount of catalyst was found to be higher than 0.05, suggesting that this parameter was insignificant. The three quadratic coefficients were all significant (P-value < 0.05). The interaction coefficients were found to be insignificant, except for the interaction between residence time and methanol-to-oil molar ratio. Furthermore, the determination coefficient (R^2) and adjusted determination coefficient (R^2_{adj}) was 0.982 and 0.950 respectively, implying a high accuracy of the model. Therefore, Equation (2) can be rewritten, as shown in the following equation (Eq. (3)) with ANOVA results, as listed in Table 4. The F-value of 33.50 ($>F_{(0.05,7,7)}=3.787$) and the significance F value of 0.00007 indicate statistical

significance. Also, the R^2 (0.971) and R^2_{adj} (0.942) values can be used to verify the model.

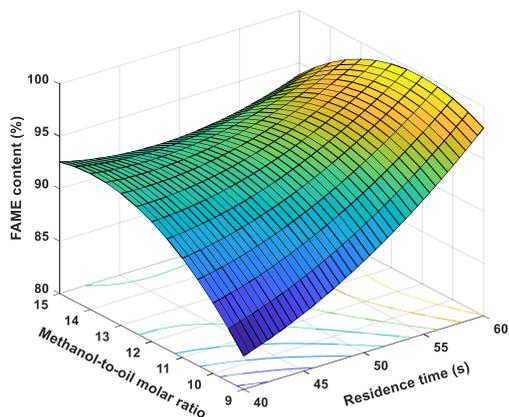
$$\begin{aligned}
 \text{FAME} (\%) = & -221.26 - 0.0975X_1 + 140.82X_2 \\
 & + 15.53X_3 - 0.1117X_1X_3 \\
 & + 0.0184X_1^2 - 23.45X_2^2 \quad (3) \\
 & - 0.3958X_3^2
 \end{aligned}$$

The 3D surface responses with 2D (2 dimensions) contour base graphs, constructed by using the calculated coefficients from Eq. (3) with two independent variables and one constant value in the quadratic equation, are shown in Fig. 5. The interactions of residence time and amount of catalyst (X_1X_2) on the FAME content are demonstrated in Fig. 5(a). At a constant methanol-to-oil molar ratio (X_3) of 11, an initial amount of catalyst (X_2) of 2.5 wt% and a residence time (X_1) of 40 s, a FAME content of 83.6% was obtained, but an increase in residence time to 60 s with any fixed amount of catalyst, increased the FAME content steadily. The reaction rate was observed to be relatively fast with the use of a conventional heat source for the transesterification reaction in this experiment, as compared with other microwave-assisted experiments [10, 28]. When the initial amount of catalyst was increased to 3.0 wt% at a residence time of 60 s, the FAME content increased to reach a maximum level. A further increase in the amount of catalyst resulted in a significant reduction in the FAME content. At the optimum amount of catalyst (3.0 wt%), the highest FAME content of 99.7% was obtained at the longest residence time (X_1) tested. Residence time greater than 60 s was not operated because the FAME content was already quite close to 100%.

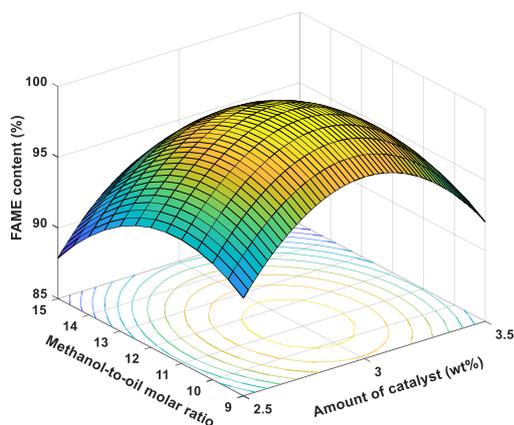
Similarly, the interaction of residence time and methanol-to-oil molar ratio (X_1X_3) affecting the FAME content at a constant 3.0 wt% of catalyst (X_2) is demonstrated in Fig. 5(b) showing that the FAME content



(a) The FAME content as a function of residence time (X_1) and amount of catalyst (X_2) at a methanol-to-oil molar ratio of 11.



(b) The FAME content as a function of residence time (X_1) and methanol-to-oil molar ratio (X_3) at 3 wt% catalyst.



(c) The FAME content as a function of amount of catalyst (X_2) and methanol-to-oil molar ratio (X_3) at residence time of 60 s

Fig. 5. Response surface plots showing the effect of three operating parameters of amount of catalyst, methanol-to-oil molar ratio and residence time. Transesterification reaction conditions: Temperature = 333 K, oscillating frequency = 4.5 Hz and amplitude = 8 mm.

reached a minimum level of 83.2% at the initial methanol-to-oil molar ratio of 9 and a residence time of 40 s. For a fixed residence time of 40 s, an increase in methanol-to-oil molar ratio to 15:1 increased the FAME content to the highest value of 92.6%. However, at the residence time of 60 s, the FAME content peaked at an approximate methanol-to-oil molar ratio of 11 and then decreased as the methanol-to-oil molar ratio was further increased. This phenomenon can be explained by the formation of emulsion due to the improvement in glycerol solubility as the methanol content increases. Although an excess amount of methanol is necessary to shift the equilibrium of the transesterification reaction, an overdose in methanol concentration can lead to the reduction in the FAME content.

Figure 5(c) demonstrates the interaction of amount of catalyst and methanol-to-oil molar ratio (X_2X_3) affecting the FAME content at a constant residence time of 60 s. For a methanol-to-oil molar ratio of 9:1 and 2.5 wt% of catalyst, a FAME content of 92.0% was attained. An increase in FAME content to 99.7% resulted from an increase in the amount of catalyst to approximately 3.0 wt% and methanol to oil molar ratio of 11. However, an increase in the amount of catalyst beyond 3 wt% caused the FAME content to reduce significantly. This was due to the presence of excess hydroxyl ion (OH^-) which reacted with triglyceride and FAME to form soap via the saponification reaction [30, 31].

3.3. Properties of purified transesterification product obtained at the optimum reaction condition

The $98.3 \pm 1.1\%$ FAME product was obtained from the transesterification experiment operated at the optimum conditions (the reaction temperature of 333 K, the methanol-to-oil molar ratio of 11:1, the amount of catalyst of 3 wt%, the oscillating frequency of 4.5 Hz and the amplitude of 8 mm). The product had viscosity of 4.6 mm^2/s which is within the appropriate range set by ASTM standard, as shown in Table 5. The acid value of the product was 0.41 mg KOH/g, which is lower than 0.5 mg KOH/g set by ASTM and EN standards, indicating that there would be no corrosion or plugging problems in usage [32]. The product had a gross calorific value of 38.9 MJ/kg. Compared to the standards, the quality of biodiesel produced in this work was met the requirement.

4. Conclusions

In the present study, WCO was used as a feedstock for the production of biodiesel using alcoholic hydroxide solutions. The results obtained from the Box-Behnken design experiments showed that for the WCO transesterification is the main reaction, and the FAME content in the product depends on operating conditions but the secondary reaction of saponification is a serious constraint. The regression analysis showed excellent fit of the quadratic model equation to the experimental data with coefficient of determination (R^2) value of 0.971 and F-value of 33.50. Both residence time and methanol-to-oil molar ratio were found to have a significant impact on the

Table 5. Properties of biodiesel (B100) produced at the optimum reaction condition compared with ASTM and EN biodiesel standards [29].

Properties	Units	B100	ASTM standard	EN standard
FAMEs content	% (m/m)	98.3±1.1	-	>96.5
Density at 288 K	kg/m ³	865.5	860 - 900	860 - 900
Viscosity at 313 K	mm ² /s	4.6	1.9 – 6.0	3.5 – 5.0
Acid value	mg KOH/g	0.4	<0.5	<0.5
Iodine value	g Iodine/100 g	119.2	<120	<120
Gross calorific value	MJ/kg	38.9	-	-
Cloud point	°C	10.0	-	-
Pour point	°C	9.0	-	-
Water content	wt%	0.05	<0.05	0.05

FAME content of the product. Using the response surface approach for the optimization of the transesterification reaction, the best conditions to give the highest FAME of 99.7% were at a residence time of 60 s, catalyst content of 3.0% and a methanol-to-oil molar ratio of 11:1. The properties such as viscosity, density, and acid value of the biodiesel product were within the standards set by ASTM.

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