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Effect of Crude Palm Oil and Waste Cooking Oil Blend Composition and Stirring Speed on Biodiesel Yield During Transesterification Using KOH Catalyst

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A B S T R A C T

The growing demand for energy and the depletion of fossil fuel reserves have accelerated the development of renewable energy sources. Biodiesel has emerged as a promising alternative because it can be produced from renewable feedstocks while reducing environmental impacts. This study investigated the effects of the composition of the crude palm oil (CPO) and waste cooking oil (WCO) blend, as well as stirring speed, on biodiesel yield and fuel properties during alkaline transesterification using a potassium hydroxide (KOH) catalyst. Five feedstock compositions consisting of 100:0, 75:25, 50:50, 25:75, and 0:100 (CPO:WCO) were evaluated at stirring speeds of 400 and 600 rpm. The transesterification process was carried out at 60°C for 60 min using a methanol to oil molar ratio of 6:1 and 1 wt.% KOH catalyst. Biodiesel products were characterized based on yield, density, kinematic viscosity, acid value, calorific value, cetane number, and fatty acid methyl ester (FAME) composition using gas chromatography mass spectrometry (GC-MS). The results demonstrated that both feedstock composition and stirring speed significantly affected biodiesel production. Increasing the proportion of waste cooking oil improved biodiesel yield, while increasing stirring speed enhanced mass transfer between methanol and oil, leading to higher conversion efficiency. The highest biodiesel yield of 80% was obtained at a CPO:WCO ratio of 25:75 with a stirring speed of 600 rpm. The produced biodiesel exhibited density, viscosity, acid value, calorific value, and cetane number within the requirements of the Indonesian National Standard (SNI 7182:2015). GC-MS analysis confirmed a FAME content of 79.18%, indicating effective transesterification. These findings demonstrate that optimizing feedstock composition and mixing intensity can improve biodiesel production efficiency while promoting the utilization of waste cooking oil as a sustainable renewable energy resource.

Contribution to Sustainable Development Goals (SDGs):

SDG 7: Affordable and Clean Energy

SDG 12: Responsible Consumption and Production

SDG 13: Climate Action

1. INTRODUCTION

1.1. Research Background

The increasing global demand for energy, together with the continuous depletion of fossil fuel reserves, has accelerated the development of renewable and sustainable energy resources. The extensive use of petroleum-based fuels has contributed significantly to greenhouse gas emissions, environmental degradation, and concerns over long-term energy security.

Consequently, renewable fuels have become an important strategy for reducing dependence on fossil resources while supporting sustainable economic development [1].

Among various renewable fuels, biodiesel has attracted considerable attention because it is biodegradable, non-toxic, renewable, and compatible with conventional diesel engines with little or no modification. Biodiesel consists mainly of fatty acid methyl esters (FAME) produced through the transesterification of triglycerides with short-chain alcohols in the presence of a



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catalyst. Compared with petroleum diesel, biodiesel produces lower emissions of carbon monoxide, hydrocarbons, sulfur oxides, and particulate matter, making it a cleaner alternative fuel [2], [3].

Indonesia has significant potential for biodiesel production, as it is one of the world's largest producers of crude palm oil (CPO). CPO has a high triglyceride content, making it an excellent feedstock for biodiesel synthesis. However, the increasing utilization of edible vegetable oils for biofuel production has raised concerns regarding production costs and competition with food resources. Therefore, alternative feedstocks with lower economic value have become increasingly attractive for biodiesel production [4].

Waste cooking oil (WCO) is one of the most promising alternative feedstocks because of its low cost, abundant availability, and environmental benefits. Improper disposal of WCO causes water and soil pollution, whereas converting it into biodiesel supports waste valorization and the circular economy. Nevertheless, repeated heating during cooking increases the free fatty acid (FFA) content and promotes oxidation, hydrolysis, and polymerization reactions that may reduce biodiesel quality and conversion efficiency. Blending CPO with WCO is expected to combine the advantages of both feedstocks by improving fuel quality while reducing production costs and environmental impacts [5], [6].

Besides feedstock characteristics, operating conditions strongly influence biodiesel production efficiency. Stirring speed is one of the most critical parameters because methanol and vegetable oil naturally form two immiscible phases. Proper agitation increases interfacial contact between reactants, enhances mass transfer, accelerates triglyceride conversion into fatty acid methyl esters, and ultimately improves biodiesel yield. Therefore, optimization of feedstock composition and stirring speed is essential for achieving efficient biodiesel production and obtaining fuel properties that satisfy the Indonesian National Standard (SNI 7182:2015) [7], [8].

Although numerous studies have investigated biodiesel production from CPO or WCO individually, studies examining the combined effects of CPO and WCO blend composition together with stirring speed under identical transesterification conditions remain limited. Moreover, comprehensive evaluation of biodiesel yield and fuel properties, including density, kinematic viscosity, acid value, calorific value, cetane number, and FAME composition determined by gas chromatography-mass spectrometry (GC-MS), has rarely been reported simultaneously. This research was therefore conducted to address these limitations by evaluating the interaction between feedstock composition and stirring speed under controlled operating conditions [8], [9].

1.2. Literature Review

Biodiesel is a renewable fuel composed primarily of fatty acid methyl esters produced through the transesterification of triglycerides with methanol or other short-chain alcohols in the presence of homogeneous or heterogeneous catalysts. Biodiesel has gained considerable attention because it reduces greenhouse gas emissions, improves fuel lubricity, and is biodegradable, making it an environmentally friendly substitute for petroleum diesel [2], [3].

Crude palm oil is one of the most widely used biodiesel feedstocks owing to its high triglyceride content, favorable fatty acid composition, and abundant availability in tropical countries. Biodiesel derived from CPO generally exhibits good oxidative stability, acceptable viscosity, and satisfactory cetane number. However, the relatively high price of edible palm oil has prompted researchers to investigate alternative low-cost feedstocks that can maintain comparable fuel quality [4].

Waste cooking oil has become an attractive raw material because it is inexpensive and widely available as household and industrial waste. Converting WCO into biodiesel not only reduces production costs but also minimizes environmental pollution associated with improper waste disposal. Nevertheless, repeated heating during cooking increases FFA content and oxidation products, making pretreatment and process optimization essential to obtain high biodiesel conversion and quality [5], [6].

Among the various operating parameters that influence transesterification, stirring speed plays a crucial role in enhancing mass transfer between the immiscible methanol and oil phases. Adequate agitation increases the interfacial area between reactants, accelerates esterification and transesterification reactions, and enhances biodiesel yield. However, excessive agitation may promote emulsion formation during product separation, reducing overall process efficiency. Therefore, determining the optimum stirring speed is essential for achieving high biodiesel productivity [7].

Previous studies have demonstrated that optimizing either feedstock composition or operating conditions can significantly improve biodiesel production. However, most investigations focused on a single feedstock or evaluated process variables independently. Comprehensive studies evaluating the simultaneous effects of CPO and WCO blend composition together with stirring speed using KOH catalyst, while also assessing biodiesel quality through density, viscosity, acid value, calorific value, cetane number, and GC-MS analysis, remain limited. This research addresses that gap by investigating these parameters under identical experimental conditions to determine the optimum operating configuration for biodiesel production [8], [9].

1.3. Research Objective

This study aims to investigate the combined effects of the composition of the crude palm oil-waste cooking oil blend and stirring speed on biodiesel production via alkaline transesterification using a potassium hydroxide (KOH) catalyst. Specifically, the study evaluates the influence of feedstock composition and stirring speed on biodiesel yield, density, kinematic viscosity, acid value, calorific value, cetane number, and fatty acid methyl ester composition determined by gas chromatography-mass spectrometry (GC-MS). Furthermore, this research identifies the optimal operating conditions that produce the highest biodiesel yield while meeting the quality requirements specified in the Indonesian National Standard (SNI 7182:2015).

2. MATERIALS AND METHODS

2.1. Materials

The materials used in this study consisted of crude palm oil (CPO) obtained from a local palm oil supplier in South Sumatra, Indonesia, and waste cooking oil (WCO) collected from local

food vendors. Prior to use, the WCO was filtered to remove suspended impurities. Methanol (99.8% purity) was used as the alcohol reagent, while potassium hydroxide (KOH, analytical grade, Merck) served as the homogeneous alkaline catalyst. Distilled water was used during the washing process to remove residual catalyst, methanol, soap, and glycerol from the biodiesel product.

The initial free fatty acid (FFA) content of each feedstock mixture was determined by acid-base titration prior to transesterification to assess the suitability of the raw materials for biodiesel production. The measured FFA values ranged from 2.00% to 3.20%, depending on the blending ratio of CPO and WCO.

2.2. Experimental Design

A 2×5 factorial experimental design was employed to investigate the combined effects of the composition of the crude palm oil (CPO) and waste cooking oil (WCO) blend and stirring speed on biodiesel production via transesterification. The independent variables consisted of five feedstock compositions (100:0, 75:25, 50:50, 25:75, and 0:100, CPO:WCO) and two stirring speeds (400 and 600 rpm), resulting in ten experimental runs.

The reaction conditions were maintained constant throughout all experiments. Biodiesel production was conducted in a baffled batch stirred tank reactor using an oil volume of 1000 mL, a reaction temperature of 60°C, a reaction time of 60 min, a methanol-to-oil molar ratio of 6:1, and a potassium hydroxide (KOH) catalyst concentration of 1 wt.% based on the oil mass. Biodiesel yield, density, kinematic viscosity, acid value, calorific value, cetane number, and fatty acid methyl ester (FAME) composition determined by gas chromatography-mass spectrometry (GC-MS) were selected as the response variables. The experimental matrix is presented in Table 1.

Table 1. Experimental design used in biodiesel production.

R un	CPO: WCO	Stirr ing Spee d (rpm)	Temper ature (°C)	Ti me (mi n)	Methan ol:Oil	KO H (wt. %)
1	100:0	400	60	60	6:1	1
2	75:25	400				
3	50:50	400				
4	25:75	400				
5	0:100	400				
6	100:0	600				
7	75:25	600				
8	50:50	600				
9	25:75	600				
10	0:100	600				

2.3. Biodiesel Production Procedure

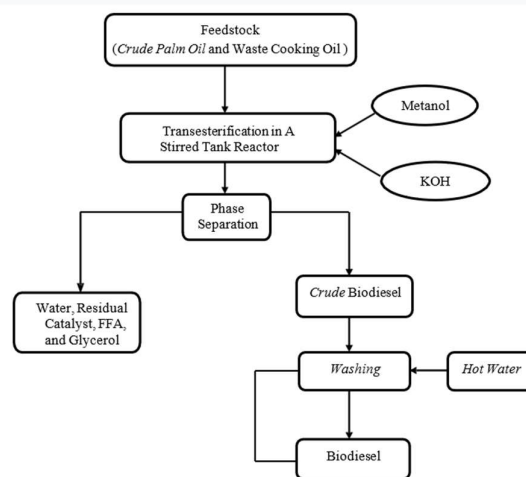


Figure 1. Flow diagram of biodiesel production through the transesterification process.

Waste cooking oil (WCO) was initially filtered to remove suspended solids and other impurities, then blended with crude palm oil (CPO) according to the experimental design. The catalyst solution was prepared by dissolving potassium hydroxide (KOH) at 1 wt.% of the oil mass in methanol until a homogeneous potassium methoxide solution was obtained.

The blended oil was transferred into a baffled batch stirred tank reactor and heated to 60°C. After reaching the desired temperature, the methanol-KOH solution was added to the reactor, and the transesterification reaction was conducted for 60 min at stirring speeds of 400 rpm and 600 rpm. The methanol-to-oil molar ratio was maintained at 6:1 throughout the experiments.

Following the reaction, the mixture was transferred to a separating vessel and allowed to settle until two distinct layers were formed. The lower glycerol layer was removed, while the upper crude biodiesel layer was collected for further purification.

The crude biodiesel was washed with hot distilled water at approximately 60°C under gentle agitation (200 rpm) for 10 min to remove residual methanol, catalyst, soap, glycerol, and other impurities. The washing process was repeated until a clear biodiesel layer was obtained. Finally, the purified biodiesel was dried to remove residual moisture before physicochemical characterization.

2.4. Biodiesel Characterization

The produced biodiesel samples were characterized to evaluate their physicochemical properties in accordance with the Indonesian National Standard (SNI 7182:2015). The evaluated parameters included biodiesel yield, density, kinematic viscosity, acid value, calorific value, cetane number, and fatty acid methyl ester (FAME) composition.

Biodiesel yield was calculated as the percentage ratio of the biodiesel volume obtained after purification to the initial oil volume used in each experiment. Density was determined using a pycnometer at room temperature, while kinematic viscosity was measured at 40°C using a rotational viscometer. The acid value was determined by titration with a standardized potassium hydroxide (KOH) solution and expressed as mg KOH g⁻¹ of

biodiesel. The calorific value was measured using a bomb calorimeter following ASTM D5865, whereas the cetane number was determined using a cetane analyzer. The chemical composition of the biodiesel was identified using gas chromatography-mass spectrometry (GC-MS) to determine the distribution of fatty acid methyl esters (FAME) produced during the transesterification process.

The measured fuel properties were compared with the quality requirements specified in SNI 7182:2015 to assess the suitability of the biodiesel produced for diesel engine applications.

2.5. Biodiesel Yield Calculation

Biodiesel yield was calculated to evaluate the conversion efficiency of the transesterification process using Equation (1).

$$\text{Yield (\%)} = \frac{\text{Volume of biodiesel produced}}{\text{Initial oil volume}} \times 100$$

where:

- Yield = biodiesel production efficiency (%)
- Volume of biodiesel produced = volume obtained after purification (mL)
- Initial oil volume = initial feedstock volume before reaction (mL)

2.6. Data Analysis

The experimental results were analyzed descriptively to determine the effects of feedstock composition and stirring speed on biodiesel yield and fuel properties. Graphical analysis and regression trendlines were employed to evaluate the relationships between process variables and biodiesel characteristics. The measured properties were then compared with the quality requirements specified in SNI 7182:2015 to determine compliance with the Indonesian biodiesel standard.

3. RESULT AND DISCUSSION

3.1. Effect of feedstock composition and stirring speed on biodiesel yield

The effects of crude palm oil (CPO) and waste cooking oil (WCO) blend composition together with stirring speed on biodiesel yield are presented in Figure 2. The results indicate that both feedstock composition and stirring speed significantly influenced biodiesel production. At 400 rpm, biodiesel yield increased progressively from 45% for the 100:0 CPO:WCO blend to 65% for pure WCO (0:100). A similar trend was observed at 600 rpm, where the yield increased from 60% to a maximum of 80% at the 25:75 CPO:WCO blend before slightly decreasing to 78% for pure WCO.

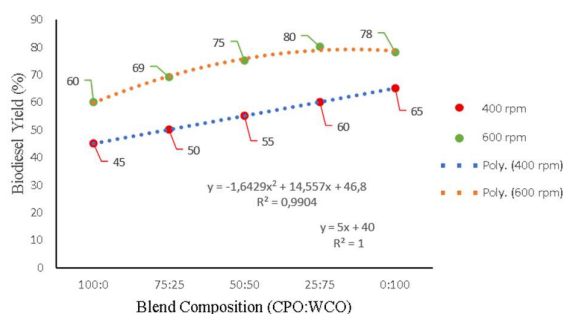


Figure 2. Effect of CPO:WCO blend composition and stirring speed on biodiesel yield.

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The gradual increase in biodiesel yield with increasing WCO proportion up to the 25:75 blend indicates that an appropriate combination of CPO and WCO created favorable conditions for the transesterification reaction. Feedstock composition affects several physicochemical properties, including viscosity, free fatty acid (FFA) content, and triglyceride composition, which directly influence biodiesel conversion efficiency. A balanced feedstock composition also improves interactions among oil, methanol, and the alkaline catalyst, resulting in more effective methyl ester formation. Similar observations have been reported by Gui *et al.* [10], who identified feedstock characteristics as a primary factor affecting biodiesel production.

The highest biodiesel yield (80%) was obtained at the 25:75 CPO:WCO blend with a stirring speed of 600 rpm. This result indicates that the selected feedstock composition provided the optimum balance between reactant properties and reaction conditions, thereby minimizing mass transfer resistance and promoting triglyceride conversion into fatty acid methyl esters (FAME). Since transesterification is a reversible reaction, efficient mixing enhances reactant contact and shifts the reaction equilibrium toward biodiesel formation, resulting in higher product yield [11].

A slight decrease in biodiesel yield was observed when pure WCO was used, from 80% to 78% at 600 rpm. Although WCO improved biodiesel production compared with pure CPO, repeated heating during cooking may generate oxidation products, polymerized compounds, and other degradation products that interfere with catalyst activity and reduce transesterification efficiency. Similar observations have been reported by Atadashi *et al.* [12], who stated that degraded compounds present in waste cooking oil can reduce biodiesel conversion efficiency.

Stirring speed also exerted a significant influence on biodiesel yield. Increasing the stirring speed from 400 rpm to 600 rpm improved biodiesel production across all feedstock compositions. For example, the yield increased from 45% to 60% for pure CPO and from 60% to 80% for the 25:75 blend. The higher stirring speed enhanced dispersion between the immiscible methanol and oil phases, increased the interfacial contact area, and improved mass transfer, thereby accelerating the transesterification reaction. These findings agree with those reported by Leung *et al.* [13], who demonstrated that appropriate agitation substantially improves biodiesel yield by enhancing mixing efficiency.

Furthermore, increasing the stirring speed from 400 rpm to 600 rpm intensified turbulence within the reactor, thereby reducing the thickness of the diffusion boundary layer surrounding the dispersed droplets. This condition enhanced the mass transfer coefficient and facilitated faster transport of methanol molecules to the triglyceride-rich phase, resulting in a higher reaction rate. Consequently, triglycerides were converted more efficiently into fatty acid methyl esters (FAME), contributing to the increased biodiesel yield observed at 600 rpm.

Regression analysis further confirmed the relationship between feedstock composition and biodiesel yield. At 400 rpm, the experimental data followed a linear relationship ($y = 5x + 40$) with an R^2 value of 1.000, indicating an excellent fit between feedstock composition and biodiesel yield. In contrast, the results at 600 rpm were better represented by a second-order polynomial equation ($y = -1.6429x^2 + 14.557x + 46.8$) with an R^2 value of 0.9904. The polynomial trend indicates that biodiesel yield increased with increasing WCO content up to the 25:75 blend,

then slightly decreased for pure WCO, suggesting an optimal feedstock composition at higher mixing intensity.

To evaluate the effectiveness of the modified reactor, additional experiments were conducted using a reactor without baffles under identical operating conditions. At 600 rpm, the baffled reactor consistently produced biodiesel yields approximately 9–11% higher than those obtained using the non-baffled reactor. The incorporation of baffles suppressed vortex formation, increased turbulence, and promoted more homogeneous mixing of oil, methanol, and catalyst, thereby reducing mass transfer limitations and enhancing triglyceride conversion. These findings are consistent with the mixing principles reported by Paul *et al.* [14].

From a hydrodynamic perspective, the presence of baffles modified the internal flow pattern by increasing axial and radial circulation while suppressing tangential swirling motion. This flow configuration improved fluid circulation throughout the reactor volume and promoted a more uniform distribution of methanol, oil, and catalyst. As a result, local concentration gradients were reduced, leading to a more efficient transesterification process and higher biodiesel yield.

Although increasing the stirring speed from 400 rpm to 600 rpm requires greater mechanical energy input, the corresponding increase in biodiesel yield demonstrates that the additional mixing energy was effectively utilized to improve reaction performance. Under the operating conditions investigated, 600 rpm provided an appropriate balance between energy consumption and biodiesel production efficiency. Further studies involving power number analysis and specific energy consumption are recommended to optimize the process at a larger scale.

The present results are consistent with the findings of Tunjungsari *et al.* [15], who reported a biodiesel yield of 78.6% from a mixture of palm oil and waste cooking oil using an alkaline catalyst. The slightly higher yield (80%) obtained in the present study is likely attributable to the optimized feedstock composition, increased stirring intensity, and the use of a baffled stirred tank reactor, which improved mixing efficiency during transesterification.

Overall, the results demonstrate that both feedstock composition and stirring speed play important roles in biodiesel production. The optimum operating condition was achieved using a 25:75 CPO:WCO blend at a stirring speed of 600 rpm in the baffled reactor, producing the highest biodiesel yield of 80%. These findings indicate that optimizing feedstock composition together with reactor mixing performance can significantly improve biodiesel production efficiency.

3.2. Effect Of Feedstock Composition On Biodiesel Density (kg/m^3)

The effect of feedstock composition on biodiesel density is presented in Figure 3. The results show that increasing the proportion of waste cooking oil (WCO) in the feedstock gradually increased the density of the produced biodiesel. The measured densities were 851.1, 874.7, 879.5, 885.4, and 888.2 kg/m^3 for the CPO:WCO blend ratios of 100:0, 75:25, 50:50, 25:75, and 0:100, respectively. All biodiesel samples satisfied the density requirement specified in SNI 7182:2015 (850–890 kg/m^3), indicating that the produced biodiesel possessed acceptable fuel quality.

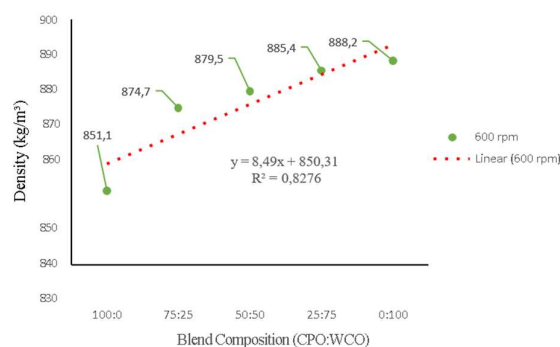


Figure 3. Effect of CPO:WCO blend composition on biodiesel density.

The progressive increase in biodiesel density with increasing WCO proportion demonstrates that feedstock composition significantly influenced the physical properties of the biodiesel. The highest density (888.2 kg/m^3) was obtained from pure WCO, whereas the lowest density (851.1 kg/m^3) was observed for pure CPO. This trend is attributed to the physicochemical changes occurring in waste cooking oil during repeated heating, including oxidation, polymerization, and thermal degradation, which produce compounds with higher molecular weight and polarity. These degradation products contribute to a more compact molecular structure, resulting in higher biodiesel density. Similar observations have been reported by Knothe [16], Knothe *et al.* [11], Ma and Hanna [17], and Demirbas [18], who concluded that feedstock composition and oxidation products strongly influence biodiesel density.

Regression analysis further confirmed the relationship between feedstock composition and biodiesel density. The experimental data fit the linear equation $y = 8.49x + 850.31$, with an R^2 of 0.8276, indicating a positive correlation between increasing WCO proportion and biodiesel density. The coefficient of determination indicates that 82.76% of the variation in density is explained by feedstock composition, while the remaining 17.24% may be attributable to other factors, including variations in feedstock characteristics, degradation products, and transesterification conditions.

The increase in biodiesel density is also supported by the GC-MS analysis, which revealed that the biodiesel was dominated by long-chain fatty acid methyl esters (FAME), including methyl oleate (29.45%), methyl palmitate (23.05%), and methyl stearate (5.29%). These compounds have relatively high molecular weights and contribute to the biodiesel's higher density. According to Knothe *et al.* [11], biodiesel containing a greater proportion of long-chain methyl esters generally exhibits higher density than biodiesel composed of shorter-chain compounds.

From a fuel-quality perspective, all biodiesel samples complied with the density requirement specified in SNI 7182:2015, indicating that blending CPO with WCO did not adversely affect this important fuel property. Instead, increasing the proportion of WCO produced biodiesel with density values that remained within the acceptable range for commercial biodiesel applications.

The density values obtained in this study (851.1–888.2 kg/m^3) are consistent with those reported in previous studies. Knothe *et al.* [11] reported that biodiesel derived from vegetable oils generally exhibits densities ranging from 860 to 900 kg/m^3 , while Sembiring *et al.* [19] reported densities of 875–889 kg/m^3 for biodiesel produced from waste cooking oil. The close agreement

between the present results and previous findings confirms that the biodiesel produced in this study has physical characteristics comparable to those of commercially acceptable biodiesel. Furthermore, the results demonstrate that waste cooking oil is a suitable alternative feedstock for biodiesel production without compromising density requirements.

3.3. Effect of Feedstock Composition on Biodiesel Kinematic Viscosity (cSt)

The effect of feedstock composition on biodiesel kinematic viscosity is presented in Figure 4. The results show that increasing the proportion of waste cooking oil (WCO) gradually reduced the kinematic viscosity of the produced biodiesel. The measured viscosities were 5.2, 5.0, 4.8, 4.5, and 4.2 cSt for the CPO:WCO blend ratios of 100:0, 75:25, 50:50, 25:75, and 0:100, respectively. All biodiesel samples complied with the viscosity requirement specified in SNI 7182:2015 (2.3–6.0 cSt), indicating that the produced biodiesel possessed suitable flow characteristics for diesel engine applications.

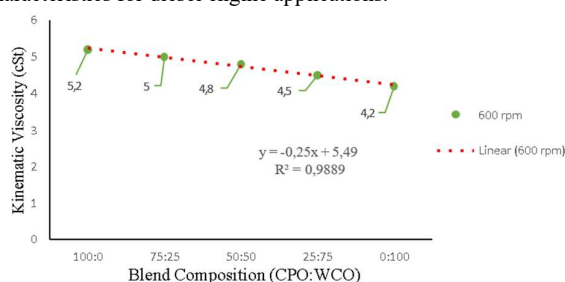


Figure 4. Effect of CPO:WCO blend composition on biodiesel kinematic viscosity.

The gradual reduction in viscosity with increasing WCO proportion indicates that feedstock composition significantly affected the flow properties of biodiesel. The highest viscosity (5.2 cSt) was obtained from pure CPO, whereas the lowest value (4.2 cSt) was observed for pure WCO. This decrease suggests that increasing the proportion of WCO improved biodiesel fluidity, thereby reducing resistance to fuel flow during injection and combustion.

The reduction in viscosity can be attributed to the transesterification process, in which triglycerides are converted into fatty acid methyl esters (FAME). Methyl esters have simpler molecular structures and exhibit weaker intermolecular interactions than triglycerides, resulting in lower viscosity. Furthermore, repeated heating of waste cooking oil alters its chemical composition through oxidation, hydrolysis, and thermal degradation. After transesterification, these modified compounds are converted into methyl esters, producing biodiesel with improved flow characteristics. Similar observations have been reported by Demirbas [18], Knothe *et al.* [11], and Ma and Hanna [17], who demonstrated that efficient triglyceride conversion significantly decreases biodiesel viscosity.

Regression analysis showed a strong linear relationship between feedstock composition and biodiesel viscosity, described by the equation $y = -0.25x + 5.4$ with an R^2 value of 0.9804. This coefficient of determination indicates that 98.04% of the variation in viscosity was explained by changes in feedstock composition, while only 1.96% was associated with other factors, including feedstock characteristics and transesterification conditions. The negative slope confirms that increasing the WCO proportion consistently reduced biodiesel viscosity.

The GC-MS analysis supports these findings by showing that the biodiesel was dominated by long-chain methyl esters, particularly methyl oleate (29.45%), methyl palmitate (23.05%), and methyl stearate (5.29%). The formation of these methyl esters indicates successful conversion of triglycerides during transesterification. According to Knothe *et al.* [11], the conversion of triglycerides into methyl esters is the primary factor responsible for the significant reduction in viscosity observed in biodiesel compared with the original vegetable oils.

The viscosity values obtained in this study (4.2–5.2 cSt) are consistent with previous reports. Demirbas [18] reported that biodiesel produced from vegetable oils generally exhibits viscosities ranging from 4.0 to 5.5 cSt, while Monde *et al.* [20] reported viscosities of approximately 4.3–4.9 cSt for biodiesel derived from waste cooking oil. The close agreement between the present study and previous investigations confirms that the transesterification process produced biodiesel with flow characteristics comparable to commercial biodiesel. Overall, increasing the proportion of WCO in the CPO:WCO blend reduced biodiesel kinematic viscosity while maintaining compliance with SNI 7182:2015. These findings demonstrate that WCO can be effectively utilized as an alternative biodiesel feedstock without compromising the viscosity requirements for commercial diesel fuel applications.

3.4. Effect of Feedstock Composition on Biodiesel Acid Value (mg KOH/g)

The effect of feedstock composition on biodiesel acid value is presented in Figure 5. The results indicate that the acid value decreased with increasing waste cooking oil (WCO) proportion up to the 25:75 (CPO:WCO) blend and then increased slightly when pure WCO was used. The measured acid values were 0.48, 0.43, 0.38, 0.24, and 0.28 mg KOH/g for the CPO:WCO blend ratios of 100:0, 75:25, 50:50, 25:75, and 0:100, respectively. All biodiesel samples satisfied the maximum acid value requirement specified in SNI 7182:2015 (≤ 0.50 mg KOH/g), indicating acceptable fuel quality.

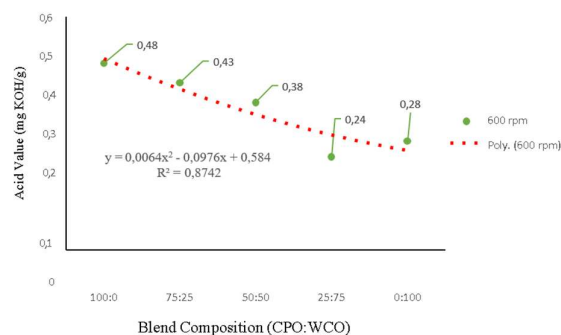


Figure 5. Effect of CPO:WCO blend composition on biodiesel acid value.

The decrease in acid value up to the 25:75 blend indicates that feedstock composition significantly affected the amount of residual free fatty acids (FFA) remaining in the biodiesel. The lowest acid value (0.24 mg KOH/g) suggests that this blend provided the most favorable conditions for the transesterification reaction, resulting in more efficient conversion of triglycerides into fatty acid methyl esters (FAME) and a lower concentration of residual FFA. According to Ma and Hanna [17], acid value is an important indicator of biodiesel quality because it reflects the

amount of free fatty acids remaining after the conversion process. Similarly, Abdullah *et al.* [21] reported that efficient transesterification significantly reduces acid value by improving triglyceride conversion and minimizing residual FFA.

A slight increase in acid value to 0.28 mg KOH/g was observed when pure WCO was used. Although this value remained well below the maximum limit specified in SNI 7182:2015, the increase suggests that repeated heating of waste cooking oil generated oxidation products and degradation compounds that slightly reduced transesterification efficiency. These degradation products may contribute to a small amount of residual free fatty acids remaining in the biodiesel.

Regression analysis further demonstrated that the relationship between feedstock composition and acid value was best described by a second-order polynomial equation, $y = 0.0064x^2 - 0.0976x + 0.584$, with an R^2 value of 0.8742. The coefficient of determination indicates that 87.42% of the variation in acid value was explained by feedstock composition, whereas the remaining 12.58% may be associated with differences in the initial FFA content, oxidation products present in the feedstock, and transesterification conditions. The polynomial trend clearly illustrates that the acid value decreased to a minimum at the 25:75 blend before increasing slightly for pure WCO, indicating that this composition provided the optimum reaction condition for minimizing residual free fatty acids.

The GC-MS analysis supports these findings by confirming that the biodiesel was dominated by long-chain methyl esters, particularly methyl oleate (29.45%), methyl palmitate (23.05%), and methyl stearate (5.29%). The high proportion of methyl esters indicates efficient triglyceride conversion during transesterification. According to Knothe *et al.* [11], a higher methyl ester content is generally associated with lower residual free fatty acid concentrations and consequently lower acid values.

The acid values obtained in this study (0.24–0.48 mg KOH/g) are consistent with those reported in previous studies. Abdullah *et al.* [21] reported acid values ranging from 0.27 to 0.45 mg KOH/g for biodiesel produced from waste cooking oil, while Monde *et al.* [20] reported acid values close to 0.28 mg KOH/g under optimized transesterification conditions. The close agreement between the present study and previous reports confirms that the biodiesel produced has acid values comparable to those of commercial-quality biodiesel.

Overall, feedstock composition significantly influenced biodiesel acid value. The lowest acid value (0.24 mg KOH/g) was achieved using the 25:75 CPO:WCO blend, while the highest value (0.48 mg KOH/g) was obtained from pure CPO. Nevertheless, all biodiesel samples complied with the SNI 7182:2015 specification, demonstrating that blending CPO with WCO can produce biodiesel with satisfactory acid value characteristics.

3.5. Effect of Feedstock Composition on Biodiesel Calorific Value (MJ/kg)

The effect of feedstock composition on the calorific value of biodiesel is shown in Figure 6. The results show that increasing the proportion of waste cooking oil (WCO) in the feedstock progressively increases the calorific value of the biodiesel produced. The measured calorific values were 29.59, 31.54, 34.12, 36.95, and 37.94 MJ/kg for the CPO:WCO blend ratios of 100:0, 75:25, 50:50, 25:75, and 0:100, respectively. The highest calorific value (37.94 MJ/kg) was observed for pure WCO,

whereas the lowest (29.59 MJ/kg) was observed for pure CPO, demonstrating that feedstock composition significantly affected the energy content of the biodiesel.

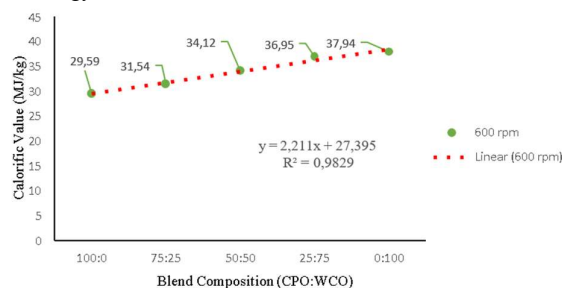


Figure 6. Effect of CPO:WCO blend composition on biodiesel calorific value.

The increase in calorific value with increasing WCO proportion indicates that biodiesel derived from WCO possessed greater combustion energy than biodiesel produced from pure CPO. This trend is closely associated with the fatty acid methyl ester (FAME) composition of the biodiesel. GC-MS analysis revealed that the biodiesel was dominated by long-chain methyl esters, particularly methyl oleate (29.45%), methyl palmitate (23.05%), and methyl stearate (5.29%). These compounds contain relatively high carbon content, which contributes to greater heat release during combustion. According to Knothe *et al.* [11], biodiesel with a higher proportion of long-chain methyl esters generally exhibits a higher calorific value due to its greater energy density.

The increase in calorific value also indicates that the transesterification process effectively converted triglycerides into methyl esters, the primary energy-producing components of biodiesel. A higher methyl ester content improves combustion characteristics and enhances the fuel's energy output. Mehta and Anand [22] reported that calorific value is strongly influenced by fatty acid composition, carbon chain length, and oxygen content, with fuels containing longer carbon chains generally producing higher combustion energy.

Regression analysis demonstrated a strong positive linear relationship between feedstock composition and biodiesel calorific value, as expressed by the equation $y = 2.211x + 27.395$, with an R^2 of 0.9829. The coefficient of determination indicates that 98.29% of the variation in calorific value is explained by changes in feedstock composition, whereas only 1.71% is attributable to other factors, including variations in fatty acid composition, methyl ester content, and transesterification conditions. The positive regression slope confirms that increasing the proportion of WCO consistently increased the energy content of the produced biodiesel.

The calorific values obtained in this study (29.59–37.94 MJ/kg) are comparable to those reported in previous studies. Mehta and Anand [22] reported that biodiesel generally exhibits calorific values in the range of 37–40 MJ/kg, while Ajis *et al.* [23] reported calorific values of 30–39 MJ/kg for biodiesel produced from vegetable oil feedstocks. The highest calorific value obtained in the present study (37.94 MJ/kg) falls within the range commonly reported for commercial biodiesel, indicating that biodiesel produced from WCO possesses competitive energy characteristics.

Overall, the feedstock composition significantly influenced the biodiesel's calorific value. Increasing the proportion of WCO resulted in a progressive increase in energy content, with the

highest calorific value achieved using 100% WCO. These findings demonstrate that waste cooking oil is a promising alternative feedstock for biodiesel production because it can produce fuel with calorific values comparable to those of commercial biodiesel while simultaneously contributing to the utilization of waste resources.

3.6. Effect Of Feedstock Composition On Biodiesel Cetane Number

The effect of feedstock composition on biodiesel cetane number is presented in Figure 7. The results indicate that increasing the proportion of waste cooking oil (WCO) progressively increased the cetane number of the produced biodiesel. The measured cetane numbers were 52.0, 54.7, 61.6, 67.9, and 72.4 for the CPO:WCO blend ratios of 100:0, 75:25, 50:50, 25:75, and 0:100, respectively. All biodiesel samples exceeded the minimum cetane number requirement specified in SNI 7182:2015 (≥ 51), demonstrating excellent ignition quality.

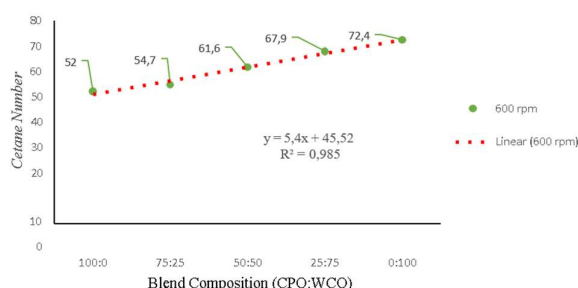


Figure 7. Effect of CPO:WCO blend composition on biodiesel cetane number.

The progressive increase in cetane number with increasing WCO proportion indicates that feedstock composition significantly influenced the ignition quality of the biodiesel. The highest cetane number (72.4) was obtained from pure WCO, whereas the lowest value (52.0) was observed for pure CPO. A higher cetane number corresponds to a shorter ignition delay, resulting in faster combustion, improved combustion efficiency, and smoother engine operation.

The improvement in cetane number is closely associated with the fatty acid methyl ester (FAME) composition of the biodiesel. GC-MS analysis revealed that the biodiesel was dominated by long-chain methyl esters, particularly methyl oleate (29.45%), methyl palmitate (23.05%), and methyl stearate (5.29%). These compounds are known to exhibit favorable ignition characteristics because long-chain methyl esters generally possess higher cetane numbers than shorter-chain compounds. According to Knothe [16], carbon chain length and fatty acid structure are major factors governing the cetane number of biodiesel, while Moser [24] reported that biodiesel containing longer and more saturated fatty acid methyl esters generally exhibits superior ignition quality.

The increase in cetane number also indicates that the transesterification process effectively converted triglycerides into methyl esters. Higher methyl ester content improves fuel reactivity during combustion, thereby shortening ignition delay and enhancing combustion performance. These observations confirm that efficient transesterification contributes not only to higher biodiesel yield but also to improved fuel quality.

Regression analysis demonstrated a strong positive linear relationship between feedstock composition and cetane number,

described by the equation $y = 5.4x + 45.52$ with an R^2 value of 0.9850. The coefficient of determination indicates that 98.5% of the variation in cetane number was explained by feedstock composition, whereas the remaining 1.5% may be associated with differences in fatty acid composition, methyl ester content, and reaction conditions. The positive regression slope indicates that increasing the WCO proportion consistently improved the ignition quality of the biodiesel.

The cetane numbers obtained in this study (52.0–72.4) are comparable to values reported in previous investigations. Moser [24] reported cetane numbers ranging from 50 to 70 for biodiesel produced from vegetable oils, while Knothe [16] demonstrated that biodiesel with higher methyl ester content generally exhibits improved ignition characteristics. Furthermore, Atadashi *et al.* [12] reported that efficient transesterification and appropriate feedstock selection significantly improve biodiesel combustion quality. The slightly higher cetane number obtained in the present study (72.4) suggests that biodiesel produced from WCO possesses excellent ignition performance and is suitable for diesel engine applications.

Overall, feedstock composition significantly affected the cetane number of biodiesel. Increasing the proportion of WCO improved ignition quality, with the highest cetane number obtained from 100% WCO. Since all biodiesel samples exceeded the minimum requirements specified in SNI 7182:2015, the biodiesel produced demonstrates excellent combustion characteristics and strong potential as an alternative renewable diesel fuel.

3.7. GC-MS Analysis Of Biodiesel

The GC-MS chromatogram of the biodiesel sample produced under the optimum operating condition (25:75 CPO:WCO blend, 600 rpm, baffled reactor) is presented in Figure 8, while the identified compounds are summarized in Table 2. Several major chromatographic peaks were detected at retention times of 14.43, 16.79, 18.88, 20.56, 20.81, and 20.89 min, indicating the presence of fatty acid methyl esters (FAME), which are the principal constituents of biodiesel. The most intense peaks appeared at 20.56 min and 18.88 min, corresponding to octadecenoic acid methyl ester and hexadecanoic acid methyl ester (methyl palmitate) with relative peak areas of 29.45% and 23.05%, respectively. The presence of these compounds confirms the successful conversion of triglycerides into methyl esters during the transesterification process. According to Knothe [16], biodiesel consists primarily of mono-alkyl esters of long-chain fatty acids, and the presence of FAME is the main indicator of successful biodiesel production.

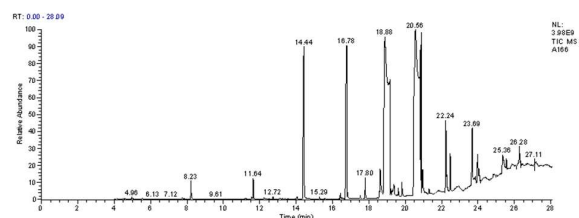


Figure 8. GC-MS chromatogram of biodiesel produced under optimum operating conditions.

Several dominant peaks were observed at retention times of 14.43, 16.79, 18.88, 20.56, 20.81, and 20.89 min, indicating the presence of long-chain fatty acid methyl esters. The largest

chromatographic peak appeared at 20.56 min with a relative area of 29.45%, followed by the peak at 18.88 min with an area of 23.05%. These results confirm that FAME compounds were the dominant products formed during the transesterification process [16].

Table 2. Major fatty acid methyl esters identified by GC-MS analysis

No	Retention Time (min)	Compound	Molecular Formula	Peak Area (%)
1	14.43	Dodecanoic acid. methyl ester (Methyl Laurate)	C13H26O2	7.80
2	16.79	Methyl tetradecanoate (Methyl Myristate)	C15H30O2	8.90
3	18.88	Hexadecanoic acid. methyl ester (Methyl Palmitate)	C17H34O2	23.05
4	20.56	Octadecenoic acid methyl ester	C19H36O2	29.45
5	20.81	9-Octadecenoic acid (Z)-. methyl ester (Methyl Oleate)	C19H36O2	4.69
6	20.89	Octadecanoic acid. methyl ester (Methyl Stearate)	C19H38O2	5.29
Total Peak Area of Major Compounds				79.18

As summarized in Table 2, six major FAME compounds were identified. The biodiesel was dominated by octadecenoic acid methyl ester (29.45%) and methyl palmitate (23.05%), while methyl myristate, methyl laurate, methyl oleate, and methyl stearate were detected in smaller proportions. The predominance of C16-C18 methyl esters is characteristic of biodiesel derived from palm oil and waste cooking oil and agrees with previous reports [11], [25].

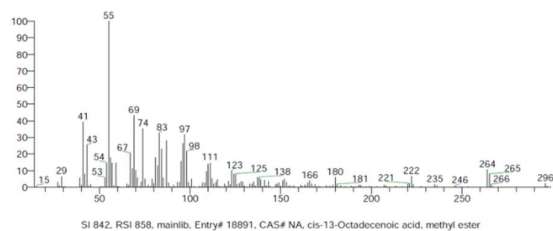


Figure 9. Mass spectrum of hexadecanoic acid methyl ester (methyl palmitate).

To verify compound identification, the mass spectrum corresponding to the peak at 18.88 min was matched with the GC-MS library database. The compound was identified as hexadecanoic acid methyl ester (methyl palmitate) with a relative area of 23.05%. This compound originates from palmitic acid, which is naturally abundant in palm oil feedstocks, confirming the successful formation of FAME during transesterification [25].

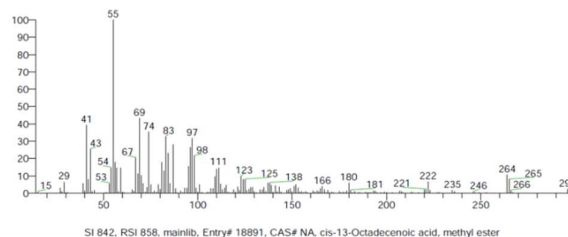


Figure 10. Mass spectrum of octadecenoic acid methyl ester.

The dominant peak at 20.56 min was identified as octadecenoic acid methyl ester, accounting for 29.45% of the total chromatographic area. This long-chain methyl ester contributes significantly to biodiesel density, calorific value, and cetane number because compounds with longer carbon chains generally possess superior combustion characteristics [11].

The identified FAME compounds accounted for 79.18% of the total chromatographic area, indicating that most triglycerides were successfully converted into methyl esters. The predominance of long-chain C16-C18 FAME explains the favorable biodiesel properties obtained in this study, including appropriate density, reduced viscosity, higher calorific value, and improved cetane number. These results are consistent with the optimum biodiesel yield (80%) achieved using the 25:75 CPO:WCO blend at 600 rpm in the baffled reactor, confirming the effectiveness of the transesterification process.

4. CONCLUSION

This study demonstrated that both feedstock composition and stirring speed significantly affected biodiesel production during transesterification. Increasing the proportion of waste cooking oil (WCO) generally improved biodiesel yield, while increasing the stirring speed from 400 to 600 rpm enhanced mass transfer and reaction efficiency. The optimum operating condition was obtained using a 25:75 CPO:WCO blend at 600 rpm in a baffled stirred-tank reactor, yielding the highest biodiesel yield of 80%. The improved reactor configuration provided more effective mixing and contributed to higher biodiesel productivity than the non-baffled reactor. The physicochemical characterization confirmed that the produced biodiesel possessed satisfactory fuel quality. The measured density ranged from 851.1 to 888.2 kg/m³, kinematic viscosity from 4.2 to 5.2 cSt, acid value from 0.24 to 0.48 mg KOH/g, calorific value from 29.59 to 37.94 MJ/kg, and cetane number from 52.0 to 72.4. All samples complied with the requirements of SNI 7182:2015. Furthermore, GC-MS analysis identified a total FAME content of 79.18%, dominated by long-chain methyl esters, confirming successful transesterification and supporting the favorable fuel properties obtained. These findings demonstrate that blending CPO with WCO, combined with efficient mixing using a baffled reactor, is an effective approach for producing high-quality biodiesel while promoting the utilization of waste cooking oil as a renewable energy resource.

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