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Research Paper

Biodiesel Production from Waste Cooking Oil Using Hydrodynamic Cavitation-Assisted Transesterification

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ABSTRACT*: The global energy crisis and the depletion of fossil fuel reserves have intensified the demand for sustainable alternative energy sources. Biodiesel derived from waste cooking oil represents a promising renewable energy source that also promotes the utilization of waste materials without competing with food resources. This study investigates the intensification of biodiesel production from waste cooking oil through hydrodynamic cavitation-assisted transesterification. Unlike conventional transesterification systems, hydrodynamic cavitation enhances interfacial mass transfer, micro-mixing efficiency, and local shear intensity, thereby accelerating triglyceride conversion into fatty acid methyl esters (FAME). The effects of NaOH catalyst concentration (1% and 1.5% w/w oil) and cavitation cycle number (15, 23, 30, 38, and 45 cycles) on biodiesel yield and physicochemical properties were systematically evaluated. Biodiesel quality was assessed based on density and viscosity according to the Indonesian National Standard (SNI 7182:2015). The results demonstrated that increasing cavitation intensity and catalyst concentration generally improved biodiesel quality and yield. Biodiesel produced using 1.5% NaOH exhibited more stable density and viscosity values across different cavitation cycles and consistently satisfied SNI requirements. The optimum condition was achieved at 1.5% NaOH and 45 cavitation cycles, resulting in a biodiesel yield of 85.72%. Compared to conventional mixing-based transesterification reported in previous studies, the hydrodynamic cavitation-assisted process demonstrated enhanced reaction efficiency through intensified turbulence generation and improved mass transfer characteristics. These findings confirm the promising potential of hydrodynamic cavitation as a process intensification technology for sustainable biodiesel production from low-quality feedstocks.*

Keywords: *Biodiesel; Waste Cooking Oil; Hydrodynamic Cavitation; Transesterification; Yield*

1. INTRODUCTION

Indonesia is endowed with abundant natural resources, including petroleum and coal. However, rapid technological advancement and population growth have led to a continuous increase in the demand for fossil fuels, while national petroleum reserves have experienced a significant decline. This imbalance poses challenges in meeting energy supply requirements and has encouraged the Indonesian government to intensify the development of renewable and environmentally friendly energy sources, particularly biodiesel. [1][2].

Biodiesel is a renewable fuel produced from lipid-based feedstocks, such as vegetable oils and animal fats, through chemical conversion processes. Biodiesel has received widespread attention as an alternative to fossil diesel fuel due to its biodegradability, lower exhaust emissions, and compatibility with conventional diesel engines. [3][4].

Between 2009 and 2022, Indonesia's biodiesel production increased from approximately 190 thousand kiloliters to 11.82 million kiloliters. Since 2020, nearly all biodiesel produced domestically has been absorbed by the domestic market, while exports have been conducted only after national demand has been fulfilled. [1]. This trend underscores the importance of ensuring the sustainable availability of biodiesel feedstocks to support long-term energy security. One potential feedstock that can be processed into biodiesel is waste cooking oil.

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As a potential resource that has not yet been optimally utilized in Indonesia, the availability of waste cooking oil was estimated to reach 16.2 million kiloliters in 2019. [1]. As a non-edible feedstock, the utilization of waste cooking oil for biodiesel production does not pose conflicts with food security, while simultaneously contributing to the reduction of environmental pollution resulting from uncontrolled disposal. [5][6]

In biodiesel production, sodium hydroxide (NaOH) is widely used as a homogeneous base catalyst due to its high catalytic activity and relatively low cost. [7]. NaOH plays a crucial role in accelerating the transesterification reaction of triglycerides into fatty acid methyl esters (FAME), where reaction performance is strongly influenced by catalyst concentration and the applied operating conditions. In addition to the catalyst, methanol serves as the alcohol reactant that reacts with triglycerides to form FAME and glycerol. Methanol is selected due to its high reactivity, relatively low cost, and its ability to produce biodiesel with physical properties that meet established standards. The methanol-to-oil ratio is a critical parameter, as it affects the reaction conversion and the yield of biodiesel produced; an excessively low ratio can reduce conversion, whereas an excessively high ratio can complicate the final product separation process. [8][9][10].

Nevertheless, optimization of these chemical parameters alone has not been fully capable of overcoming the limitations of conventional transesterification processes, particularly with respect to relatively long reaction times and limited mass transfer between immiscible reactants. To address these constraints, hydrodynamic cavitation has been introduced as an effective process intensification technique. The formation and collapse of cavitation bubbles generate localized turbulence and high shear forces, thereby significantly enhancing mixing and mass transfer. These conditions contribute to accelerated reaction kinetics and improved biodiesel yield. [11][12]. The hydrodynamic cavitation-assisted transesterification system used in this study is illustrated in Figure 1.

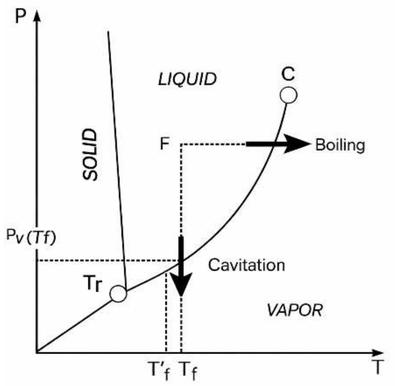


Figure 1. Schematic diagram of a hydrodynamic cavitation–assisted transesterification system.

As illustrated in Figure 1, hydrodynamic cavitation occurs as a result of a local pressure reduction within the fluid flow, leading to the formation of vapor-filled cavities. When these cavities are transported to regions of higher pressure, they collapse rapidly, generating intense shock waves, microjets, and transient conditions of high temperature and pressure. [13][14][15]. This extreme microenvironment enhances mass transfer and interfacial contact between immiscible reactants, thereby accelerating the transesterification reaction.

As a consequence of this phenomenon, the mechanical and physicochemical effects induced by cavitation promote the disruption of triglyceride molecules, enhance interphase dispersion, and contribute to emulsion destabilization as well as the removal of suspended impurities. Consequently, hydrodynamic cavitation acts as an effective process intensification mechanism that not only enhances the kinetics of the transesterification reaction but also has the potential to improve the quality of the resulting biodiesel.

Nevertheless, despite the extensive application of hydrodynamic cavitation in biodiesel production, limited studies have systematically investigated the synergistic interaction between cavitation cycle intensity and NaOH catalyst concentration using Indonesian waste cooking oil feedstock under controlled operating conditions. Previous studies have primarily focused on either catalyst optimization or cavitation application separately, while mechanistic evaluation of process intensification through simultaneous variation of cavitation cycles and catalyst concentration remains insufficiently explored. Therefore, this study provides a more comprehensive engineering analysis regarding the role of hydrodynamic cavitation in enhancing interfacial mass transfer, reaction kinetics, and biodiesel conversion efficiency.

2. RESEARCH METHOD

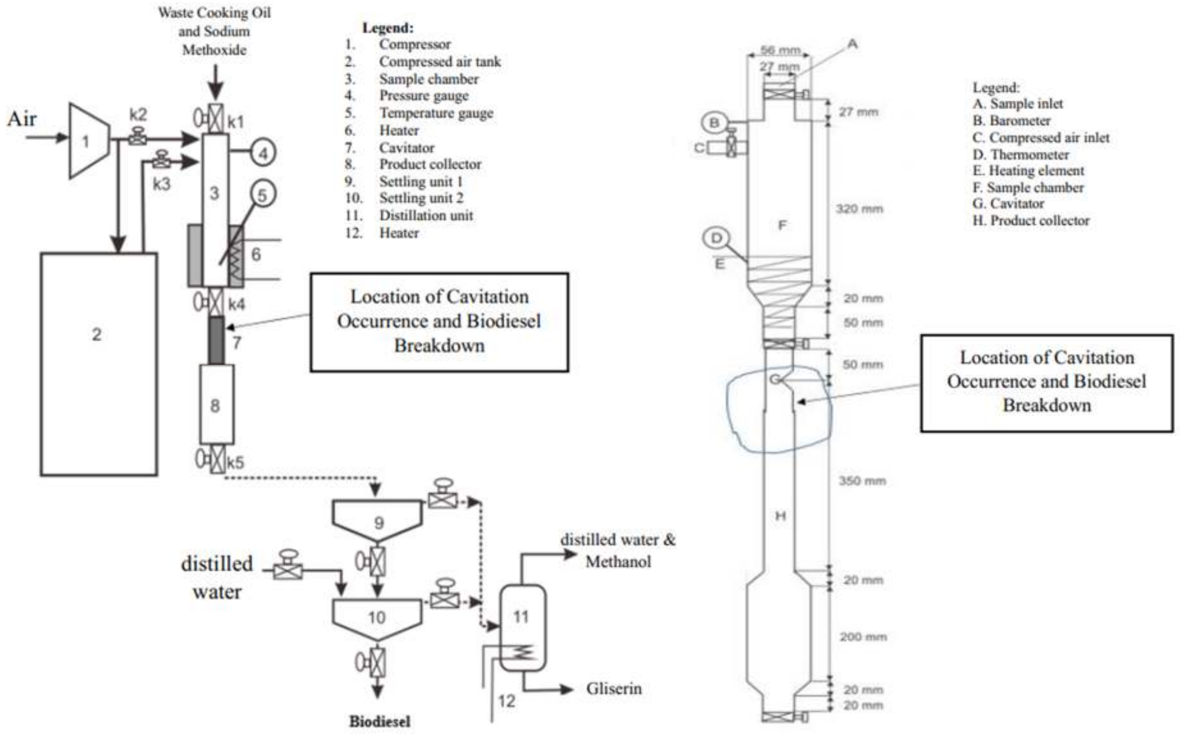
2.1 Materials

The primary materials used in this study included 200 mL of waste cooking oil obtained from street food vendors selling pecel lele along Sidomoyo Street, Godean District, Sleman Regency, Special Region of Yogyakarta, which was utilized as the biodiesel feedstock. Methanol was employed as the alcohol reactant in the transesterification process at a volume of 50 mL (Merck, ≥99.8%). Sodium hydroxide (NaOH) was used as a homogeneous base catalyst with concentration variations of 1% and 1.5% based on oil weight (Merck, ≥98%). In addition, 100 mL of distilled water was used as a supporting medium in the hydrodynamic cavitation process. [8]

2.2 Equipment

The transesterification process was carried out using a hydrodynamic cavitation reactor, which has been widely demonstrated to be effective as a process intensification method in biodiesel production. [11] Cavitation is generated when the reactant mixture is passed through a nozzle driven by a pressure differential, resulting in a local pressure drop within the fluid flow. This condition induces the formation and collapse of cavitation bubbles, which subsequently enhance mixing and mass transfer during the transesterification process.

Figure 2 presents a schematic diagram of the hydrodynamic cavitation extraction apparatus.



(a) (b)

Figure 2. Hydrodynamic cavitation extraction apparatus: (a) overall schematic of the hydrodynamic cavitation–based biodiesel extraction system; (b) detailed view of components 3 and 8 as indicated in Figure 2(a).

2.3 Research Procedure

This study employed a hydrodynamic cavitation–assisted transesterification process to enhance mixing and mass transfer between immiscible reactants. [11]. The mixture of waste cooking oil, methanol, and NaOH catalyst was circulated through the cavitation reactor, resulting in a local pressure reduction that triggered the formation of cavitation bubbles. [16]. The NaOH catalyst concentration was varied at 1% and 1.5% based on oil weight to evaluate its effect on the performance of the transesterification reaction. In addition, the number of cavitation cycles applied was varied at 15, 23, 30, 38, and 45 cycles. Prior to yield determination, biodiesel was purified through settling and washing stages to remove residual methanol, catalyst, soap, and glycerol.

2.3.1 Pre-treatment of Waste Cooking Oil

Pre-treatment was conducted to reduce the content of impurities and free fatty acids (FFA), as high FFA levels can inhibit base-catalyzed transesterification through saponification reactions. [17] The oil was first filtered to remove suspended solids, after which the FFA content was determined using an acid–base titration method. [8]

The reduction of FFA content was carried out through an adsorption process using activated carbon at 2% (w/w relative to oil), which has been proven effective in improving oil quality as a biodiesel feedstock. [18]. After the adsorption process, the treated oil was separated and subsequently used in the transesterification stage.

2.3.2 Hydrodynamic Cavitation-Assisted Transesterification

After the pre-treatment stage, the transesterification process was conducted using a methanol-to-oil molar ratio of 6:1 at a temperature of 60 °C and a pressure of 4 atm. These operating conditions were selected to enhance methanol reactivity while preventing evaporation during the cavitation-assisted process. [16][19]. Hydrodynamic cavitation was applied as a process intensification method to enhance mass transfer and accelerate the reaction compared to conventional stirring methods. [11]

2.3.3 Hydrodynamic Cavitation Parameters

To strengthen the analysis of hydrodynamic cavitation performance, several important engineering parameters were considered, including pressure drop, flow characteristics, and cavitation intensity. Cavitation intensity is strongly influenced by local pressure reduction occurring within the nozzle section, which promotes vapor bubble formation and subsequent collapse. The cavitation phenomenon can be quantitatively represented by the cavitation number (Cv), defined as:

$$\mathrm{Cv} = \frac{P_2 - Pv}{1/2\rho v^2} \quad \text{..........} \quad (1)$$

where P_2 is downstream pressure (Pa), Pv is vapor pressure (Pa), ρ is fluid density (kg/m³), and v is fluid velocity (m/s). Lower cavitation number values indicate stronger cavitation intensity. In hydrodynamic cavitation systems, enhanced cavitation intensity contributes to improved turbulence generation, interfacial disruption, and mass transfer efficiency during transesterification. Detailed hydrodynamic parameters such as flow rate distribution, Reynolds number, nozzle velocity profile, and specific energy consumption were not comprehensively evaluated in the present study due to experimental limitations.

2.4 Analytical Methods

Biodiesel quality analysis included density and viscosity measurements conducted in accordance with the Indonesian National Standard SNI 7182:2015. Biodiesel yield was calculated based on the ratio of the mass of biodiesel produced to the mass of the initial waste cooking oil. The experimental data were analyzed to evaluate the effects of NaOH catalyst concentration and the number of cavitation cycles on the physical properties and yield of the biodiesel.

2.4.1 Free fatty Acid (FFA) Analysis

The free fatty acid (FFA) content of the waste cooking oil was determined using an acid–base titration method. This analysis was conducted to evaluate the suitability of the oil as a feedstock for the transesterification process. The FFA value was calculated using the following equation: [20]

$$FFA = \frac{V_{NaOH} \times N_{NaOH} \times BM_{fatty\ acid}}{m_{waste\ cooking\ oil} \times 1000} \times 100\% \ \ldots\ldots\ldots\ldots \quad (2)$$

where VNaOH is the volume of NaOH solution used (mL), NNaOH is the normality of NaOH (eq/L), MW is the molecular weight of the fatty acid (assumed as oleic acid), and m_oil is the mass of the oil sample (g).

2.4.2 Density Analysis

Biodiesel density was measured using a pycnometer in accordance with the standard testing procedure. The density value was calculated based on the difference in the pycnometer mass when filled and empty, divided by the pycnometer volume, as expressed by the following equation: [21]

$$\rho = \frac{m}{V} = \frac{m_{pikno0} - m_{pikno1}}{V} \ \ldots\ldots\ldots\ldots \quad (3)$$

where ρ is the density of biodiesel (kg/m³), m_pycnometer_empty and m_pycnometer_filled are the masses of the pycnometer without and with the sample, respectively, and V is the volume of the pycnometer.

2.4.3 Viscosity Analysis

The kinematic viscosity of biodiesel was determined using a capillary viscometer. The viscosity value was calculated using a comparative method with distilled water as the reference fluid : [22]

$$\eta_x = \eta_{water} \times \left(\frac{t_x \cdot \rho_x}{t_{water} \cdot \rho_{water}} \right) \ \ldots\ldots\ldots\ldots \quad (4)$$

where η_x is the kinematic viscosity of biodiesel, t_x and t_water are the flow times of biodiesel and distilled water, respectively, and ρ_x and ρ_water are the densities of biodiesel and distilled water.

2.4.4 Biodiesel Yield Analysis

Biodiesel yield was calculated based on the ratio of the mass of biodiesel produced to the initial mass of waste cooking oil used, following the method commonly employed in biodiesel studies [21][23][24] :

$$yield\ (\%) = \left(\frac{m\_b}{m\_m}\right) \times 100 \ \ldots\ldots\ldots\ldots \quad (5)$$

where m_b is the mass of biodiesel obtained (g) and m_oil is the mass of waste cooking oil used (g).

2.4.5 Statistical Analysis

All experiments were conducted in triplicate, and the obtained data were statistically analyzed. Error analysis was incorporated into graphical presentations using standard deviation error bars to evaluate data variability. The relatively small error values obtained indicate good experimental reproducibility and measurement consistency.

3. RESULTS AND DISCUSSION

3.1 Pre-Treatment Results of Waste Cooking Oil

The initial characteristics of the waste cooking oil used as a biodiesel feedstock need to be determined to assess its suitability for base-catalyzed transesterification. The analyzed parameters included density, viscosity, and free fatty acid (FFA) content before and after pre-treatment, as well as the visual characteristics of the oil. The results of the waste cooking oil characterization are presented in Table 1.

Table 1. Specifications of Waste Cooking Oil as Biodiesel Feedstock

No.	Characteristics	Results
1.	Density (kg/m³)	909.376
2.	Viscosity (cSt)	10.047
3.	(FFA, %) before *pre-treatment*	1.700
4.	(FFA, %) after *pre-treatment*	0.600
5.	Color	Dark Brown

Based on the results presented in Table 1, the waste cooking oil shows potential for use as a biodiesel feedstock after appropriate pre-treatment. The obtained density of the waste cooking oil was 909.376 kg/m³, which falls within the typical density range of waste cooking oil reported in several studies, i.e., 0.900–0.936 g/mL (900–936 kg/m³) [25]. This density value reflects the formation of high-molecular-weight degradation products resulting from repeated frying processes, such as oil oxidation and polymerization [5].

In addition to density, the measured viscosity of the waste cooking oil was 10.047 cSt, which is considerably higher than that of conventional diesel fuel. This high viscosity is generally associated with oxidation, polymerization, and thermal degradation occurring during repeated heating and use of the oil. Such conditions can interfere with atomization and combustion performance, thereby necessitating the transesterification process to convert waste cooking oil into biodiesel with improved flow properties [22].

Furthermore, the pre-treatment results indicated that the free fatty acid (FFA) content was successfully reduced from 1.70% to 0.60%, thereby meeting the recommended limit for base-catalyzed transesterification [16]. This reduction in FFA content plays a crucial role in minimizing soap formation and improving phase separation, which ultimately contributes to an increased biodiesel yield [17].

In addition to these quantitative parameters, the dark brown color of the waste cooking oil indicates thermal degradation and the presence of impurities formed during repeated frying cycles. Although color does not directly affect the transesterification reaction, this parameter is related to the presence of oxidation products and contaminants that require pre-treatment before the biodiesel synthesis process [5]

Overall, these results confirm that waste cooking oil has the potential to be effectively utilized as a biodiesel feedstock, provided that adequate pre-treatment is performed to reduce the free fatty acid content and improve the physicochemical properties of the oil prior to the transesterification stage.

3.2 Physical Characteristics of the Produced Biodiesel

The physical characteristics of the biodiesel produced in this study were visually observed to assess color and the presence of sediment as preliminary indicators of biodiesel quality. These observations provided an initial insight into the purity and stability of the biodiesel obtained from the production process. The biodiesel samples from this study are shown in the following figure.

Figure 3 illustrates the visual characteristics of biodiesel produced through hydrodynamic cavitation–assisted transesterification. In this method, cavitation generates extremely high local energy, which enhances mixing and accelerates the reaction between the oil and methanol phases. The hydrodynamic cavitation–

assisted transesterification approach has been widely demonstrated to improve mass transfer efficiency compared to conventional transesterification methods, particularly in heterogeneous systems involving immiscible reactants. [11][16][26][27]

Figure 3. Visual characteristics of the biodiesel produced in this study: **(a)** Biodiesel sample with 1% NaOH concentration; **(b)** Biodiesel sample with 1.5% NaOH concentration.

In line with this mechanism, in Figure 3(a), the biodiesel with 1% NaOH catalyst concentration exhibited color variations across different numbers of cavitation cycles. The presence of sediment in the sample subjected to 15 cavitation cycles indicates that, at low cavitation intensity, the mixing and transesterification reaction were not yet optimal. The sediment observed at the bottom of the container reflects gravitational separation between glycerol and other heavy impurities formed during the reaction, due to the higher density and viscosity of glycerol compared to biodiesel. [5][22]

Figure 3(a) shows that the purified biodiesel with 1% NaOH catalyst concentration still exhibited visual differences across varying numbers of cavitation cycles. In the sample subjected to 15 cavitation cycles, a sediment layer with a gel- or jelly-like texture was observed at the bottom of the container. This finding indicates that at low cavitation intensity, the conversion of triglycerides to methyl esters had not proceeded optimally, even after the purification step. The formed sediment was not the result of glycerol or reaction impurity separation, but originated from the inherent characteristics of the waste cooking oil feedstock, which tends to produce heavy fractions or portions of oil or fatty acids that do not fully react with the base catalyst (NaOH) and alcohol, and thus do not convert into biodiesel (methyl esters). [8][17][21] Conversely, increasing the number of cavitation cycles to 45 at 1% NaOH concentration resulted in biodiesel with a more uniform color and free of sediment (Figure 3a). This indicates that higher cavitation intensity enhances the cavitation effect, thereby improving mixing efficiency and facilitating more effective phase separation. As a result, residual glycerol, soap, and other impurities can be better separated from the biodiesel phase.

Meanwhile, for biodiesel with 1.5% NaOH catalyst concentration (Figure 3b), all samples exhibited relatively uniform color, and no sediment was observed across all variations in the number of cavitation cycles. This condition indicates that increasing the catalyst concentration accelerates the transesterification reaction rate, enabling methyl ester formation and product separation to proceed more optimally even at lower cavitation intensity.

Therefore, the visual observation results shown in Figure 3 confirm that the synergy between catalyst concentration and hydrodynamic cavitation intensity plays a crucial role in determining the initial quality of the produced biodiesel. A 1.5% NaOH concentration yielded biodiesel that was more homogeneous and visually stable, whereas at 1% NaOH, a higher number of cavitation cycles was required to obtain biodiesel with similar visual characteristics.

3.2.1 Biodiesel Viscosity

The graph of kinematic viscosity measurements of biodiesel produced using NaOH catalysts at concentrations of 1% and 1.5% across different numbers of cavitation cycles is presented in Figure 4.

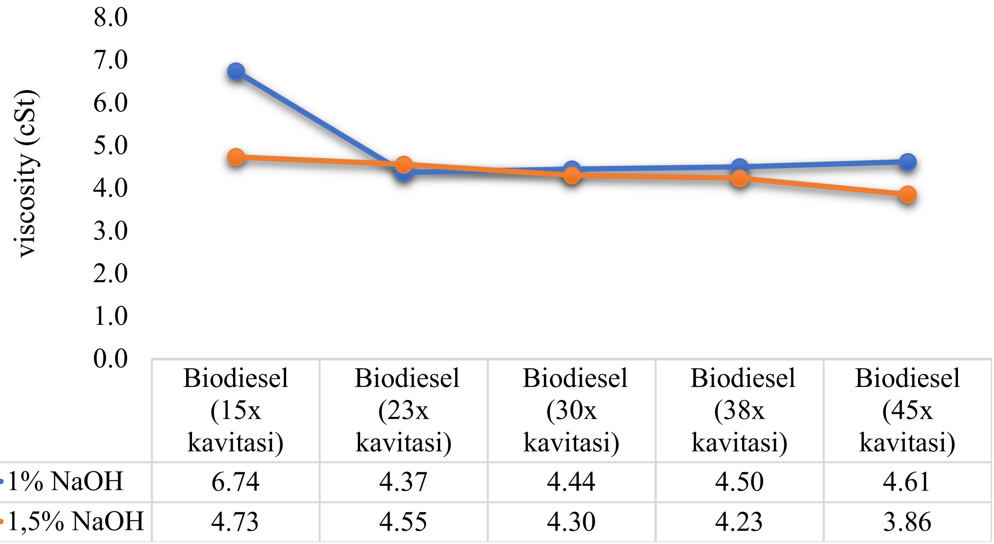


Figure 4. Kinematic Viscosity Test Results of Biodiesel Produced Using NaOH Catalyst at Concentrations of 1% and 1.5%

Figure 4 shows the effect of the number of cavitation cycles and NaOH catalyst concentration on the kinematic viscosity of biodiesel produced through hydrodynamic cavitation-assisted transesterification. In general, for both catalyst concentration variations, a tendency for viscosity reduction is observed as the number of cavitation cycles increases. This trend reflects an increase in transesterification reaction efficiency as well as a decrease in the fraction of high-viscosity compounds due to the conversion of triglycerides into fatty acid methyl esters.

The reduction in biodiesel viscosity with increasing cavitation cycles can be mechanistically associated with enhanced interfacial disruption between the methanol and oil phases. The collapse of cavitation bubbles generates intense microjets and localized shear forces, which promote finer dispersion of methanol droplets within the triglyceride phase.

This phenomenon substantially increases interfacial area and accelerates transesterification kinetics, thereby reducing the concentration of unreacted triglycerides and intermediate glycerides that contribute to higher viscosity.

In line with this tendency, at the use of 1% NaOH catalyst, the biodiesel produced at low cavitation intensity (15×) exhibited the highest viscosity, namely 6.74 cSt. This relatively high viscosity value indicates that the transesterification process had not proceeded optimally, such that unreacted triglycerides or partial glycerides were still present. A similar condition has also been demonstrated in previous studies, where limitations in cavitation intensity or catalyst concentration hindered interfacial contact and reaction kinetics, thereby preventing the conversion from occurring completely. [28]

Furthermore, increasing the number of cavitation cycles to 23× resulted in a significant decrease in viscosity to 4.37 cSt. This reduction indicates an improvement in conversion efficiency due to the intensification of mass transfer and microscale mixing generated by hydrodynamic cavitation. Nevertheless, a further increase in the number of cavitation cycles was not accompanied by a continuous decrease in viscosity. At 45× cavitation, the biodiesel viscosity slightly increased to 4.61 cSt, indicating the presence of an optimum cavitation condition in the 1% NaOH system. This phenomenon may be associated with the possible occurrence of partial emulsification or the re-dispersion of glycerol under excessive cavitation, as has also been demonstrated in previous hydrodynamic cavitation studies. [28][29]

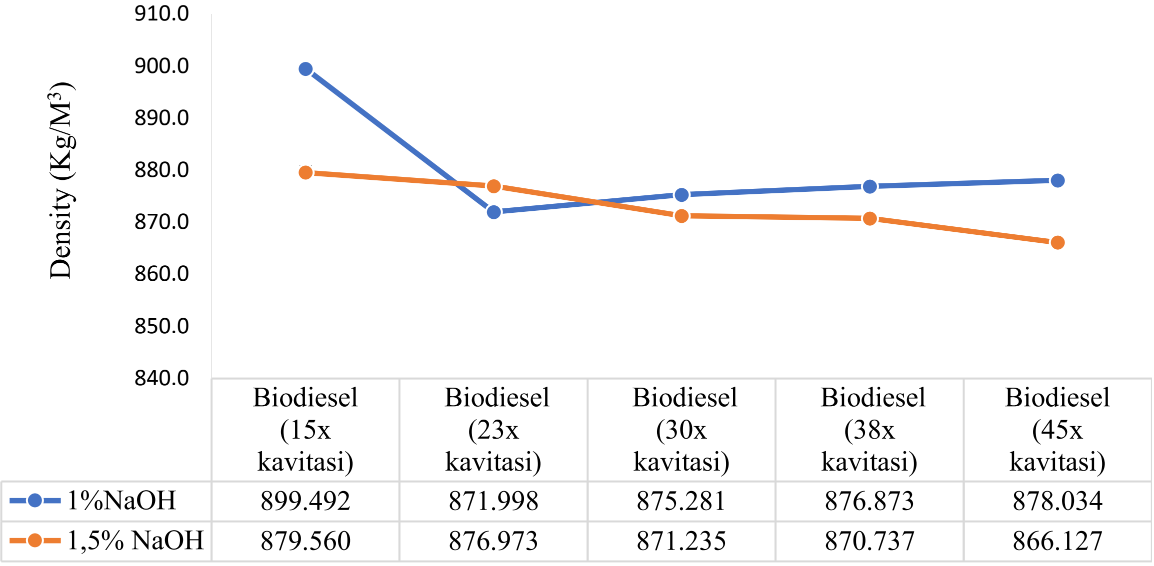
In contrast, biodiesel produced using 1.5% NaOH catalyst exhibited more stable viscosity behavior and a monotonically decreasing trend throughout the investigated range of cavitation cycles. The lower initial viscosity value, 4.73 cSt at 15× cavitation, indicates that the transesterification process had proceeded more effectively from the early stage. This finding confirms the role of higher catalyst concentration in accelerating the reaction and enhancing the utilization of cavitation energy. Furthermore, as the number of cavitation cycles increased to 45×, the viscosity of biodiesel in the 1.5% NaOH system continued to decrease and reached a minimum value of 3.86 cSt. This consistent decreasing trend indicates that the combination of higher catalyst concentration and increased cavitation intensity was able to promote more complete triglyceride conversion and minimize residual oil content. A similar viscosity reduction pattern has also been widely demonstrated in the literature, confirming the presence of a synergistic interaction between catalyst availability and hydrodynamic cavitation intensity. [29]

Therefore, the decrease in biodiesel viscosity observed in this study can be directly attributed to the effectiveness of the hydrodynamic cavitation-assisted transesterification process. The high shear forces, local turbulence, and transient mixing generated by cavitation significantly enhance interfacial contact between oil and methanol, thereby accelerating the formation of methyl esters, which possess lower viscosity compared to the original oil. [28] Most biodiesel samples produced in this study satisfied the viscosity requirements of SNI 7182:2015. However, the biodiesel produced using 1% NaOH at 15 cavitation cycles exhibited a viscosity value slightly above the standard limit, indicating incomplete transesterification under insufficient cavitation intensity. [29]

The relatively small standard deviation values obtained from triplicate experiments indicate good reproducibility and consistency of the hydrodynamic cavitation-assisted transesterification process.

3.2.2 Biodiesel Density

The graph of biodiesel density test results produced using NaOH catalyst at concentrations of 1% and 1.5% under varying numbers of cavitation cycles is presented in Figure 5.



	Biodiesel (15x kavitasi)	Biodiesel (23x kavitasi)	Biodiesel (30x kavitasi)	Biodiesel (38x kavitasi)	Biodiesel (45x kavitasi)
1%NaOH	899.492	871.998	875.281	876.873	878.034
1,5% NaOH	879.560	876.973	871.235	870.737	866.127

Figure 5. Results of biodiesel density testing produced using NaOH catalyst at concentrations of 1% and 1.5%.

Figure 5 presents the effect of the number of cavitation cycles on the density of biodiesel produced using NaOH catalyst at concentrations of 1% and 1.5%. In general, for both catalyst systems, a decreasing trend in density is observed with increasing cavitation cycles. This trend indicates an improvement in transesterification process efficiency due to the intensification of hydrodynamic cavitation conditions, which promote the conversion of high–molecular-weight triglycerides into fatty acid methyl esters (FAME) with lower molecular weight and density. The observed density reduction reflects the progressive conversion of high-molecular-weight triglycerides into lower-density methyl esters. Hydrodynamic cavitation enhances this conversion through intensified micro-mixing and improved reactant contact efficiency. Furthermore, improved glycerol separation at higher cavitation intensity contributes to lower residual impurity content within the biodiesel phase.

In line with this trend, for biodiesel produced using 1% NaOH catalyst, the highest density was observed at low cavitation intensity, namely 899.492 kg/m³ at 15× cavitation. This relatively high density value indicates that the transesterification process and phase separation had not proceeded optimally, resulting in the presence of unreacted triglycerides or residual glycerol in the biodiesel phase. Subsequently, increasing the number of cavitation cycles to 23× caused a significant decrease in density to 871.998 kg/m³, reflecting improved conversion efficiency due to intensified mass transfer and more effective interfacial mixing.

Nevertheless, a further increase in the number of cavitation cycles in the 1% NaOH system was not followed by a continuous decrease in density. At 45× cavitation, the biodiesel density slightly increased to 878.034 kg/m³. This minor fluctuation indicates the attainment of an optimum cavitation condition, in which prolonged cavitation exposure may trigger secondary effects such as partial emulsification or the re-entrainment of glycerol into the biodiesel phase, as also reported in previous studies on hydrodynamic cavitation systems with relatively low catalyst concentrations. [16][22] In contrast, biodiesel produced using 1.5% NaOH catalyst exhibited a more systematic and monotonically decreasing density throughout the investigated range of cavitation cycles. The lower initial density 879.560 kg/m³ at 15× cavitation, indicates that the transesterification process proceeded more effectively from the early stage compared to the 1% NaOH system. This finding confirms the role of greater catalyst availability in accelerating the reaction and enhancing the utilization of cavitation energy.

Furthermore, as the number of cavitation cycles increased to 45×, the density of biodiesel in the 1.5% NaOH system continued to decrease and reached a minimum value of 866.127 kg/m³. This consistent decreasing trend indicates that the combination of higher catalyst concentration and increased cavitation intensity was able to promote more complete triglyceride conversion and improve phase separation behavior. A similar density reduction pattern is also consistent with previous studies that associate this phenomenon with a reduced content of residual glycerides in biodiesel. [22].

Therefore, the decrease in biodiesel density observed in this study can be attributed to enhanced micro-mixing, high shear forces, and local turbulence generated during hydrodynamic cavitation. These effects significantly increase interfacial contact between oil and methanol and accelerate the transesterification reaction. [16] The biodiesel density values obtained were within the range of biodiesel densities commonly reported in the literature and are associated with improved fuel injection characteristics, spray atomization, and enhanced combustion performance, which are important for biodiesel applications in diesel engines. [22]

The relatively small standard deviation values obtained from triplicate experiments indicate good reproducibility and consistency of the hydrodynamic cavitation-assisted transesterification process.

3.3 Biodiesel Yield (%*Yield*)

To evaluate the effects of the number of cavitation cycles and catalyst concentration on the performance of the transesterification process, the biodiesel yield produced using the hydrodynamic cavitation method was measured. The observed parameters included the mass of waste cooking oil as the feedstock, the volume of methanol, the mass of glycerol as a by-product, and the mass of biodiesel formed at varying cavitation cycles and NaOH catalyst concentrations. The results of the biodiesel yield tests are presented in Table 2.

Table 2. Biodiesel Yield Results Obtained Using the Hydrodynamic Cavitation Method.

Cavitation Cycles	NaOH Concentration (%)	Moles of Waste Cooking oil (mol)	Moles of Methanol (mol)	Glycerol Mass (gr)	Biodiesel Mass (gr)
Biodiesel 15x Cavitation	1%	0.205	1.23	73.936	107.939
Biodiesel 23x Cavitation	1%	0.205	1.23	31.020	150.856
Biodiesel 30x Cavitation	1%	0.205	1.23	46.207	135.669
Biodiesel 38x Cavitation	1%	0.205	1.23	37.191	144.684
Biodiesel 45x Cavitation	1%	0.205	1.23	58.950	122.925
Biodiesel 15x Cavitation	1.5%	0.205	1.23	69.292	112.584
Biodiesel 23x Cavitation	1.5%	0.205	1.23	59.099	122.776
Biodiesel 30x Cavitation	1.5%	0.205	1.23	39.864	142.011
Biodiesel 38x Cavitation	1.5%	0.205	1.23	35.591	146.284
Biodiesel 45x Cavitation	1.5%	0.205	1.23	25.972	155.903

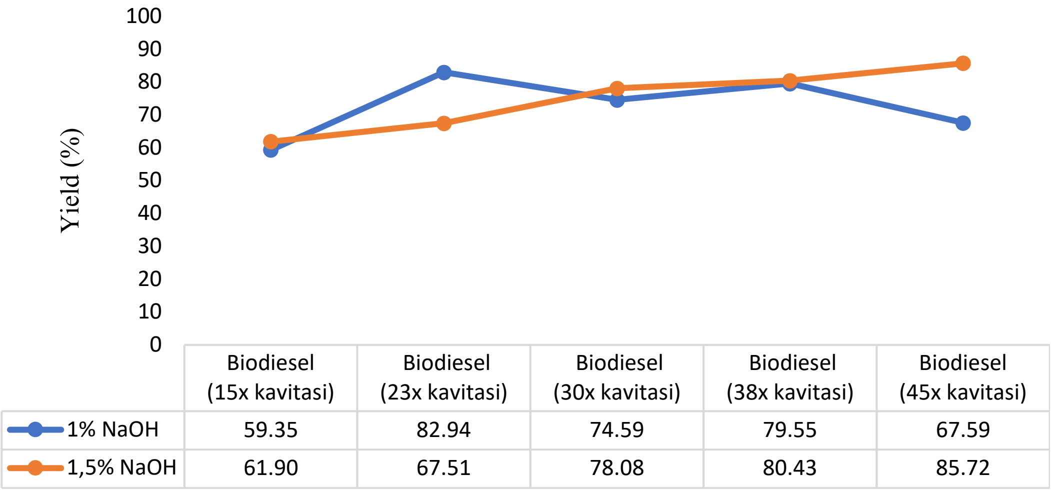
Based on Table 2, it can be observed that variations in the number of cavitation cycles and NaOH catalyst concentration have a significant effect on the mass of biodiesel produced. In both catalyst systems, the mass of waste cooking oil and the volume of methanol were kept constant; therefore, changes in the mass of biodiesel and glycerol formed can be directly attributed to the effectiveness of the transesterification process as influenced by cavitation intensity and catalyst availability.

The superior performance observed at 1.5% NaOH concentration indicates the presence of a synergistic interaction between catalyst availability and cavitation-induced process intensification. Adequate catalyst concentration ensures sufficient active sites for reaction progression, while hydrodynamic cavitation minimizes diffusion limitations commonly encountered in conventional transesterification systems. For the 1% NaOH catalyst, the biodiesel mass increased from 107.939 g at 15 cavitation cycles to 150.856 g at 23 cycles, indicating enhanced triglyceride conversion due to intensified mixing and improved mass transfer. However, at higher cavitation cycles, the biodiesel mass exhibited fluctuations, with decreases observed at 30 and 45 cycles. This pattern indicates the presence of an optimum cavitation condition, where excessive cavitation may trigger secondary effects such as the re-dispersion of glycerol into the biodiesel phase or reduced catalyst effectiveness at lower concentrations, thereby inhibiting a continuous increase in yield.

In contrast, at a 1.5% NaOH catalyst concentration, increasing the number of cavitation cycles showed a more consistent trend toward increased biodiesel mass. The biodiesel mass gradually increased from 112.584 g at 15 cycles to 155.903 g at 45 cycles, accompanied by a significant decrease in glycerol mass. This trend indicates that higher catalyst availability enables more effective utilization of cavitation energy, thereby promoting more complete transesterification reactions and which may contribute to improved biodiesel–glycerol phase separation behavior.

Overall, the results presented in Table 2 confirm a synergistic interaction between hydrodynamic cavitation intensity and NaOH catalyst concentration in determining biodiesel yield. Increasing the number of cavitation cycles strengthens micro-mixing and accelerates the reaction, while higher catalyst concentrations ensure sufficient availability of active sites to achieve optimal triglyceride conversion. These findings reinforce the potential of hydrodynamic cavitation as an effective process intensification method for biodiesel production from waste cooking oil.

The overall efficiency of the hydrodynamic cavitation process is ultimately reflected in the percentage of biodiesel yield obtained. This yield comparison provides a direct indication of the extent to which the waste cooking oil feedstock is chemically converted into biodiesel relative to the by-product glycerol. The graph of biodiesel yield (% yield) produced using NaOH catalyst concentrations of 1% and 1.5% at varying numbers of cavitation cycles is presented in Figure 6.



	Biodiesel (15x kavitasi)	Biodiesel (23x kavitasi)	Biodiesel (30x kavitasi)	Biodiesel (38x kavitasi)	Biodiesel (45x kavitasi)
1% NaOH	59.35	82.94	74.59	79.55	67.59
1,5% NaOH	61.90	67.51	78.08	80.43	85.72

Figure 6. Biodiesel yield (% yield) produced using NaOH catalyst at concentrations of 1% and 1.5%.

Based on Figure 6, the use of 1.5% NaOH catalyst demonstrates superior performance compared to 1% NaOH in the hydrodynamic cavitation-assisted transesterification system. At a NaOH concentration of 1.5%, the biodiesel yield increased consistently with increasing cavitation cycles and reached a maximum value of 85.72% at 45 cycles. In contrast, at a NaOH concentration of 1%, the highest yield was achieved only at 23 cycles, with a value of 82.94%, followed by a significant decrease at higher cavitation cycles, indicating limitations in catalyst effectiveness under these conditions.

More specifically, in the system using 1.5% NaOH catalyst, the biodiesel yield increased from 61.90% at 15 cavitation cycles to 67.51% at 23 cycles, and then continued to increase to 78.08% at 30 cycles and 80.43% at 38 cycles, before reaching the maximum value of 85.72% at 45 cycles. This sustained increasing pattern indicates that higher cavitation intensity effectively enhances mass transfer and reaction kinetics, thereby enabling increasingly optimal triglyceride conversion at this catalyst concentration.

Meanwhile, the lower yield observed at low cavitation cycles, particularly at 15 cycles, is associated with incomplete transesterification reactions. This condition is characterized by the presence of glycerol and intermediate components that have not been optimally converted, which directly reduces the fraction of biodiesel formed. As the number of cavitation cycles increases, the mass of glycerol produced tends to decrease, indicating an increasing completeness of triglyceride conversion into fatty acid methyl esters.

Although increasing catalyst concentration has the potential to promote soap formation due to saponification reactions, particularly when using waste cooking oil containing free fatty acids, the results of this study indicate that process intensification through hydrodynamic cavitation may help reduce the negative impact of soap formation through enhanced mixing and improved reactant dispersion. Consequently, the system continues to exhibit an increase in biodiesel yield up to the highest cavitation cycle investigated [30].

Overall, the maximum yield of 85.72% obtained in this study demonstrates the promising potential of hydrodynamic cavitation-assisted transesterification for enhancing biodiesel production efficiency under the investigated operating conditions. This finding confirms that the combination of a 1.5% NaOH catalyst concentration and high cavitation intensity represents an optimum condition for producing biodiesel with high yield, even when using lower-quality feedstocks such as waste cooking oil. [27]

The relatively small standard deviation values obtained from triplicate experiments indicate good reproducibility and consistency of the hydrodynamic cavitation-assisted transesterification process.

3. CONCLUSIONS

This study demonstrates that waste cooking oil can be effectively converted into biodiesel through a transesterification reaction using NaOH catalyst assisted by hydrodynamic cavitation. The application of hydrodynamic cavitation enhances the mixing between oil and methanol, thereby allowing the reaction to proceed more efficiently. This is evidenced by the increased biodiesel yield and the improvement in the physical properties of the produced fuel with increasing numbers of cavitation cycles.

Based on the experimental results, the optimum operating condition was obtained at a NaOH catalyst concentration of 1.5% with 45 cavitation cycles, resulting in the highest biodiesel yield of 85.72%. In addition to achieving the maximum yield, the biodiesel produced under these conditions also exhibited favorable physical properties. The biodiesel density ranged from 866–871 kg/m³, and the kinematic viscosity ranged from 3.86–4.30 mm²/s, all of which fall within the limits specified by the Indonesian National Standard (SNI 7182:2015), namely a density of 850–890 kg/m³ and a kinematic viscosity of 2.3–6.0 mm²/s. These results indicate that the produced biodiesel meets the required fuel quality standards.

Furthermore, the results of this study confirm that the combination of catalyst concentration and cavitation intensity strongly influences both biodiesel yield and quality. When using a 1% NaOH catalyst, increasing the number of cavitation cycles did not always result in a consistent increase in yield. In contrast, at a 1.5% NaOH catalyst concentration, the biodiesel yield increased more steadily with increasing cavitation cycles without compromising fuel quality. Visual observation of the settling process also showed a clear separation of heavy impurities, indicating that the transesterification reaction proceeded effectively, although further purification processes are still required.

Although the produced biodiesel satisfied the density and viscosity requirements of SNI 7182:2015, additional characterization including acid value, water content, flash point, and FAME composition analysis using GC-MS or GC-FID is still required to comprehensively validate fuel quality.

The findings of this study confirm that hydrodynamic cavitation acts as an effective process intensification technology by enhancing turbulence generation, interfacial disruption, and mass transfer efficiency during transesterification. Compared to conventional transesterification systems reported in previous literature, hydrodynamic cavitation-assisted transesterification demonstrated improved mixing efficiency and enhanced biodiesel conversion behavior. In addition, the produced biodiesel exhibited physical properties that generally complied with SNI 7182:2015 standards, indicating the promising potential of hydrodynamic cavitation technology for sustainable and environmentally friendly biodiesel production.

This study primarily focused on the effects of cavitation cycles and catalyst concentration on biodiesel production performance. Detailed hydrodynamic parameters such as cavitation number, Reynolds number, flow behavior, and specific energy consumption were not comprehensively evaluated and should be investigated in future studies. Furthermore, energy efficiency analysis, cavitation number optimization, and reactor scale-up are still required to evaluate the industrial applicability of hydrodynamic cavitation-assisted biodiesel production.

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