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Biodiesel production of WCO-neem oil and mixed using pilot plant scale with ultrasound

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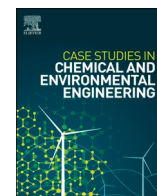
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Case Report

Biodiesel production of WCO-neem oil and mixed using pilot plant scale with ultrasound and overhead stirred and characteristic of emissions in fire tube boiler

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ABSTRACT

The boiler is one of the industrial machines that consumes the most fuel and boilers are significant contributors to air pollution. This study aims to compare the physicochemical properties of biodiesel a mixture of WCO oil and neem oil (70:30) using a pilot plant scale with different types of stirring (overhead and ultrasound). Subsequently, the produced biodiesel was tested for fuel consumption rate and exhaust emissions generated from combustion in a fire-tube boiler. The optimum yield was found using an ultrasound stirrer at a temperature of 60 °C, KOH loading 2 w/w%, with an molar ratio methanol to oil of 12:1 and a reaction time of 75 min, which is 98.70 %. The addition of neem oil to WCO oil increased the oxidative stability and reduced the pour point, and cloud point of WCONOME, by 184.85 %, 16.67 %, and 52 % respectively. Next, the ultrasound stirrer biodiesel with higher density and kinematic viscosity compared to the overhead stirrer, although the flash point and cetane number were lower. Increasing the biodiesel ratio in diesel fuel reduced exhaust emissions (CO, CO₂, and HC) produced by the boiler. Interestingly, the exhaust emissions of WCONOME were lower than compared to palm biodiesel POME30. The physicochemical properties of WCONOME biodiesel have met the ASTM 6751 standard. Finally, biodiesel from a mixture of waste cooking oil and neem oil has great potential to replace diesel fuel as a fire-tube boiler fuel for generating green energy.

1. Introduction

The growing demand for energy in different sectors has deepened dependence on fossil fuels. Nonetheless, Rising oil prices, decreasing petroleum reserves, and growing environmental concerns have driven efforts to explore cleaner and more sustainable energy solutions [1]. As energy consumption rises, petroleum reserves diminish, and emissions of various pollutants, such as NO_x, CO, CO, volatile organic compounds (VOCs), and particulate matter (PM), increase, leading to a range of environmental issues [2]. Currently, the use of alternative fuels is demonstrated to be an efficient method for minimizing adverse environmental effects [3]. Biodiesel has gained significant interest as a renewable and eco-friendly fuel, mainly due to its combustion properties that are similar to those of diesel [4]. Moreover, biodiesel is biodegradable, contains little to no sulfur and aromatic compounds, has a high flash point, and enhances engine longevity due to its exceptional

lubricating properties [5], high cetane number, and environmental friendliness [6].

As we search for alternative energy sources, biodiesel has proven to be a particularly promising and sustainable option. This renewable fuel comes from natural, biodegradable materials like animal fats [7], vegetable oils, and non-edible such as *Carthamus lanatus* L [8], *Celastrus paniculatus* [9], *P. maderaspatensis* [10], *Ipomoea cairica* [11], and waste cooking oil (WCO) [12]. In biodiesel production, the cost of the primary feedstock is a crucial factor affecting the development of bio-fuels, as it accounts for more than 70 % of the total biodiesel cost [13]. Lately, non-edible oils like waste cooking oils (WCO) have been extensively utilized as feedstock to lower the costs of biodiesel production [14]. Conversely, utilizing WCO as a raw material for biodiesel production offers two significant advantages: it provides a cost-effective and readily available resource for generating renewable biodiesel, and it can help mitigate environmental problems like clogged drains and

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sewers [15]. Biofuels offer potential as a renewable alternative in various transportation sectors by making use of waste materials like used cooking oil [3]. Nevertheless, one of the difficulties in utilizing WCO for biodiesel production is its cold flow properties [16]. The high viscosity at lower temperatures can make it challenging to pump and inject WCO into a diesel engine. The Cold flow properties are crucial, particularly for biodiesel, as poor quality can cause significant issues [16]. Low-quality cold flow properties may result in pure biodiesel solidifying in fuel lines or clogging filters in cold environments [17].

However, biodiesel exhibits low oxidative stability because the oils and fats used as raw materials contain unsaturated fatty acids that are prone to oxidation, particularly when exposed to light and oxygen [5]. Biodiesel consists of fatty acid methyl esters (FAME), which include both saturated and unsaturated types. While higher levels of saturated FAME enhance oxidative stability, they tend to reduce cold flow properties [4]. Using antioxidants is widely recognized as an effective way to enhance the oxidative stability of biodiesel. These antioxidants are generally classified into natural and synthetic types [18]. Besides, Combining oils with varying fatty acid compositions can significantly enhance the cold flow properties of biodiesel [19]. Currently, researchers are making significant progress, focusing on the application of blending oils to improve the physicochemicals of biodiesel. Therefore, to improve the physicochemical properties, researchers have recently reported blending oils with other suitable potential oils before transesterification, as demonstrated in Table 1:

Mechanical agitation requires significant energy and extended processing time to effectively carry out the methylation or ethylation of triglycerides. To overcome these challenges, ultrasound technology has become a widely adopted alternative to mechanical methods in the transesterification process [37]. The sonochemical effect results from ultrasonic cavitation, which plays a crucial role in speeding up chemical reactions. It enhances the mixing of reactants, leading to more favourable reaction conditions [38]. The ultrasound-assisted process generates tiny bubbles through continuous expansion and compression in the solvent. These bubbles continue to grow, accumulating energy until they eventually collapse, a phenomenon known as acoustic cavitation [39]. The ultrasound-assisted synthesis technique employed in this study

significantly accelerates the reaction process, reducing the overall reaction time by 68 % [38], Decreases the alcohol-to-oil ratio (by 16.67 %–25 %), catalyst quantity (by 20 %–25 %), phase separation time, and energy consumption (by 33 %–50 %) are observed, along with enhancements in biodiesel conversion and yield (by 4 %–27.9 %) [40].

Numerous studies have successfully utilized ultrasonic techniques in biodiesel production. Some researchers use ultrasonic stirring in the process of synthesizing various feedstocks into biodiesel, such as *Sterculia foetida* [41], *Ceiba pentandra* [42], *Ricinus communis* oil, and cottonseed cooking oil [28], WCO [43], *Thlaspi arvense* L [44], *Schleichera triguga* [45], rice bran [39], *Carica candamarcensis* [46]. Masri et al. [47] compared the esterification reaction in biodiesel production using ultrasonic and mechanical stirrers with SO_3H -functionalized dicationic ionic liquids. They found that the reaction conversion with ultrasonography was 1.5 times higher compared to the mechanical stirring method. The application of ultrasound with various types of feedstock in biodiesel production is presented in Table 2:

The boiler is one of the industrial machines that consumes the most fuel [53]. Boilers and heating furnaces are significant contributors to air pollution. As major stationary pollution sources, boilers are essential for supplying water or steam for various chemical processes. They generate water vapour used to power electric generators and provide heat for everyday needs, leading to substantial fuel consumption and emissions [54]. Research has been conducted during the combustion of diesel and diesel-biodiesel blend fuels. While there is an abundance of studies focusing on biofuel blends in internal combustion engines, only a limited number of studies have been done on their use in boilers. Nonetheless, it is essential to maintain efficient, sustainable, and cost-effective operation of boilers [55].

Recently, the use of biodiesel as a fuel for boilers has been explored. For example, Ghorbani et al. [56] compared the emissions produced by diesel and biodiesel in an experimental-scale boiler. They mentioned that the emissions of CO , CO_2 , and SO_2 from biodiesel were lower compared to diesel, but they increased NO_x emissions. Moreover, the use of biodiesel in a semi-industrial boiler increases the flame temperature by 17 % but shortens the flame length [57]. Lin and Wu [54] investigated the emissions produced by industrial boilers using biodiesel

Table 1
Impact of blending agents on the physicochemical of different biodiesel types.

Type of Biodiesel	Density at 20 °C	Kinematic viscosity at 40 °C	Flashpoint (°C)	Cetane number	Cold Flow			Oxidation Stability (h)	Ref.
					CP (°C)	PP (°C)	CFPP (°C)		
WCO-Calophyllum inophyllum	878	5.12	163.5	–	4	3	4	18.14	Milano [20]
WCO-Canola	890	5.5	1	–	4.4	–2.4	–	7.56	Kassem [21]
WCO-30 % S.oleosa	857	4.459	172	–	21	9	–	6.8	Suherman [22]
WCO-microalgae	890	4.5	180	–	–	–2.5	–	–	Beyene [23]
WCO-castor	875	5.76	133	–	–	8	–	9.2	Kodgire [24]
Jatropha, Karanja, and Palm oils	–	–	–	–	–	–	–	8.5	Kumar [25]
Castor and karanja oils	944.7	7.83	160	–	13	12	–	–	Kumar [26]
sunflower and castor (60:40)	–	–	–	–	–	–	–	7.55	Chellappa [27]
WCO-sesame	879.5	5.08	78.50	–	–	–	–	6.5	Bajwa [16]
Ricinus communis oil and used cottonseed cooking oil	875	6.24	150.3	–	–	7	–	8.6	Kodgire [28]
castor seed oil and waste fish oil (70:30)	898	3.61	84	56.97	5	–2	–	–	Fadhil [29]
Jatropha curcas–Ceiba pentandra	831.2	3.95	196	58	0.5	0.5	–2	10.01	Dharma [30]
Palm oil-Castor	–	5.61	219	–	11.85	–	–	–	Mejia [31]
Calophyllum inophyllum–palm	880	4.5	160	–	–	–	–	114.2	Damanik [32]
algae-Jatropha Curcas oil	–	4.1	115	–	–	–	–	–	Narula [33]
Palm and sesame oils	880	4.42	150	53.37	7.94	3.80	–1.77	6.89	Mujtaba [34]
Carica papaya, Citrus sinensis, and Hibiscus sabdariffa seed oils	872	1.82	130	64.4	–	–12	–	–	Adepoju [35]
Pongamia and neem oils	820	4.5	178	66.26	8	–2	–	–	Vinayaka [36]

Table 2
Review of the application of ultrasonic stirring in biodiesel production.

Catalyst	Catalyst	Reaction condition				yield	Ref
		Temperature (°C)	Time (h)	Catalyst loading	Methanol to oil molar ratio		
WCO	CaDG	60	0.5	1 %	9:1	93.5 %	[43]
WCO	nano-photocatalyst (ILNPC)		1	6,9 %	12:1	99,5 %	[15]
WCO	Zr-Ca/Kaolin(T)-U(300)	110	3	10 %	20:1	99,0 %	[48]
WCO	NaOH	65	0.67	1 %	12:1	97,05 %	[38]
WCO	KOH	55	2	3 %	1:6	91,5 %	[49]
WCO-castor oil	KOH	50	0.15	0.52 %	8.42:1	93,12 %	[24]
Sterculia foetida	KOH	55	1	1 %	12:1	99.41 %	[41]
Ceiba pentandra	NBPA	65	0.75	2 %	10:1	94.62 %	[42]
Palm and sesame oils	KOH	60	0.5	0.70 %	1:3	95,89 %	[34]
Ricinus communis oil and used cottonseed cooking oil	CaO	50	0.2	2.8 %	9,7:1	92.11 %	[28]
Ricinus communis oil and used cottonseed cooking oil	CaO	60	0.2	2.8 %	9.7:1	92.11 %	[28]
Thlaspi arvense L	CH ₃ ONa	60	2.5	1.36 %	9.5:1	95.91 %	[44]
Schleichera triguga rice bran	Ba(OH) ₂	50	1.3	3 %	9:1	96.8 %	[45]
	KOH	60	0.13	1 %	60 %	97.74 %	[39]
Carica candamarcensis	KOH	60	0.5	1 %	60 %	96.2 %	[46]
Spent Coffee Ground	KOH	60	3	4 %	30:1	97.11 %	[50]
Jjoba oil	ZnFe ₂ O ₄ @TiO ₂	55	0.5	2,89 %	12:1	97.56 %	[51]
Eucalyptus oil	KOH	34.31	0.12	1 %	6.36: 1	95.7 %	[52]

Table 3
Performance and emission of biodiesel-diesel blends.

biodiesel	Blends	Boiler Specification	Boiler Efficiency	Emissions						Ref
				NOx	CO	CO ₂	HC	SO ₂	EGT	
Palm biodiesel	B100	Type Vertical, water tube coil type, Steam Temperature 200 °C, Steam Pressure 10 Max	64,98 %	–	↑21 %	–	↓ 50 %	–	13,34 %↓	[58]
–	B100	horizontal fire-tube steam boiler, capacity 3 tons/hour, pressure: 10 kg/cm ² and fuel injection pressure was 2 kg/cm ²	86,6 %	↓68,9 %	–	–	–	–	–	[54]
WCO	B100	Semi-industrial boiler (C493, P.A. Hilton company, UK) and using gas Analyzer (Testo 350z).	–	–	↓ 53.7 %	13.04 %	47.84↑	–	–	[2]
Soybean and sunflower oil	B50	Using Nozzle 1.35 US gal/h–60° H KH (Hollow), the output of Power up to 150 kW, with Flow rate 4–7 l/h, fuel of acceptable viscosity 1.5–7.5 @40 mm ² /s, and outlet of fuel pressure 8–15 bar	5 %↑	15 %↑	–	7 %↓	–	–	–	[56]
sunflower	B30	hot water boiler (50 kW), using the combustion chamber was 60 cm and 34 cm	–	↓ 8 %	↓ 94.45 %	↓ 11.9 %	–	–	–	[61]
sunflower	B20	Boiler model AR/25GT ROCA, capacity 26.7 kW, capacity of water 26 L, Maximum temperature 110 °C	–	–	↓ 82.5 %	↓ 7.8 %	–	–	–	[60]
biodiesel		Thermal power 300–419 kW, Fireplace power 324–458 kW, Boiler capacity 400 L, Max. Exhaust temp 188 °C								
biodiesel	B10	Power output up to 150 kW, Flow rate of fuel 4–38 kg/h,	63,25 %	–	↓ 12.5 %	11.12 %	3.12↑	–	–	[53]
castor	B30	Burner output kW approx. 18 the pressure of oil max 13 bar, the flow rate of oil l/h max 2, compression of fan max 9 mbar, Power consumption 185/360 W	2.46 %↓	–	–	27,53 %↓	↓15,2 %	–	–	
Palm oil	B25	TYPESB 60 MMT-Fire Tube Pressure 4,5 Bar Steam Capacity 60.000 k cal/h, Temperature 150°C Dimension 650 mm, H = 1425 mm, Shell-Tube Plate SS400-10 mm thick Fire Tube Seamless Boiler ST 35,8	–	↓36.92 %	–	6.75 %↑	–	↓31.32 %	–	[62]
Palm oil		Thermal power 300–419 kW, Fire-place power 324–458 kW, Maximum thermal load 1562 kW/m ³ , Number of smoke pipes 30 N°, Diam. of the smoke pipe 1 1/2 inch, Boiler capacity 400 L		2 %↑	↓ 90 %	↓20 %	–	↓15 %		[63]
Corn oil		C492 manufactured by P.A. Hilton (England)		↑17.85 %	↓25 %	↓12.72 %	–	↓1450 %		[64]

as a fuel. The study results show that the concentrations of NO_x and SO₂ decreased significantly by 68.9 % and 99.5 %, respectively.

Furthermore, Khiraiya et al. [58] found that hydrocarbon emissions from B100 biodiesel derived from palm oil were 50 % lower compared to diesel fuel, but it increased carbon monoxide emissions by 21 %. Bazooyar et al. [59], analyzed the cost-effectiveness of operating a utility boiler power plant operating on petrodiesel, vegetable oil, biodiesel, and their typical fuel blends. Findings indicate that utilizing pure in the boiler is not cost-effective, while the performance with B5 and B20 proves to be economical. Other researchers who applied biodiesel as boiler fuel include González-González et al. [60]. They experimentally tested a mixture of biodiesel from sunflower oil and liquid fuel in a 26.7 kW capacity boiler. An increase in CO₂ and a reduction in CO and O₂ were observed. The exhaust gas emissions produced by biodiesel fuel used in the boiler as summarized in Table 3:

Therefore, this study investigates the effect of adding neem oil on improving physicochemical properties such as flash point, oxidation stability, and pour point of waste cooking oil methyl ester. The Biodiesel production was carried out using a pilot scale plant with two different types of mixers (ultrasound and overhead stirred). Additionally, the produced biodiesel was applied as a fire tube boiler. Fuel consumption and exhaust gas emissions were examined and compared with industrial biodiesel (POME30) in Indonesia.

2. Methods

2.1. Materials

In this research, waste cooking oil was sourced from restaurants in Medan City, and Neem oil was purchased in Central Java, Indonesia. The chemical reagents utilized in this study, methanol (99.8 % purity), and KOH—were obtained from Rudang Jaya, Indonesia. The POME30 oil is obtained from the fuel filling station of the State-Owned Enterprise for Oil and Gas Mining (Pertamina) in Medan City.

2.2. Biodiesel production

At first, the oil undergoes fine filtration to eliminate suspended solid particles, and afterward, the filtered waste cooking oil synthesizes biodiesel through a transesterification process. The Waste cooking oil and neem oil were mixed in a ratio of 70:30 and agitated for 10 minutes at a speed of 800 rpm. The transesterification process was carried out in a pilot plant (Capacity 25 L) at a temperature of 60 °C using KOH catalyst (1 % and 2 %) demonstrated in Fig. 1. The specifications of the ultrasound and overhead stirrers used in the transesterification process are presented in Table 4.

The agitation process was compared using an overhead stirrer (1.200 rpm) and ultrasound (20 kHz) for 75 minutes respectively, while the methanol-to-oil ratio was varied (2:1, 3:1, and 4:1 wt/wt). Following the transesterification process, the oil was transferred into a separating funnel and left overnight to separate the oil from methanol. The oil was then washed with distilled water at a temperature of 50 °C and filtered with Whatman paper. The biodiesel was then heated to a temperature of 100 °C to eliminate any remaining water and methanol in the biodiesel. The biodiesel production process of the WCO-Neem oil blend is presented in Fig. 2. Table 5: displays the apparatus and testing procedures employed to assess the physicochemical properties of the biodiesel.

2.3. Biodiesel characterization

WCONOME biodiesel was characterized using various tests, as shown in Table 5. Fourier-Transform Infrared (FTIR) analysis was conducted using a BRUKER-TENSOR 27. Gas Chromatograph-Mass Spectrometry (GC-MS) analysis was used to characterize the methyl ester composition with a Shimadzu Type QP2010 Plus. The Oxidation stability of the biodiesel was tested using a rapidOxy 100 fuel oxidation

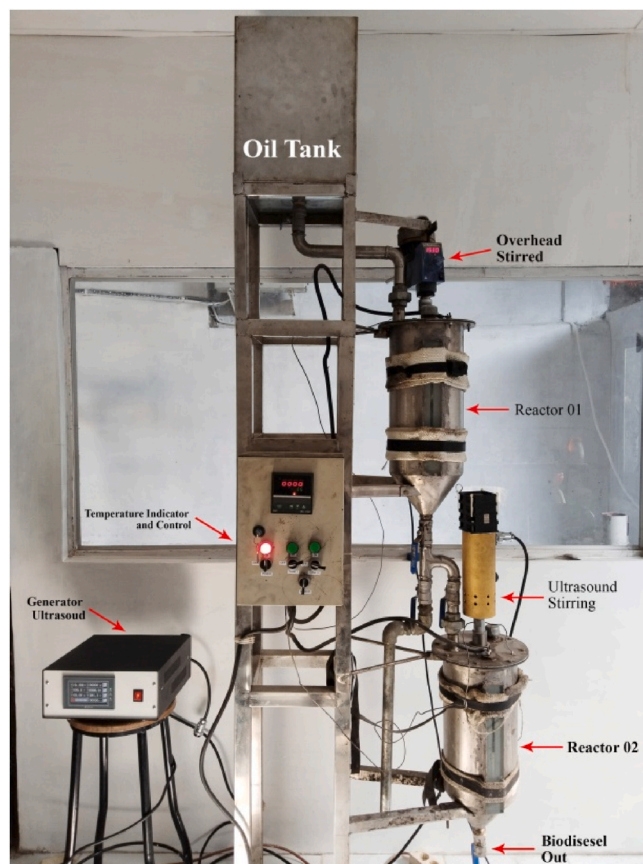


Fig. 1. Experimental setup for transesterification.

Table 4

Specification of ultrasound and overhead stirrer.

	Ultrasound	Overhead
Merk	Foshan Pulisonic Ultrasonic Technology co., Ltd	IKA RW-20
Max speed	20 kHz	2000 rpm
Display	LED	LED
Max capacity	25 L	25 L
Type of heater	Heating rod 1000 w	Heating rod 1000 w
Power	1000 w	186 w

stability tester (Anton Paar, Germany) at 110 °C with argon gas. Density and kinematic viscosity testing used an SVM 3000 viscometer for cold properties (Anton Paar, Austria). Furthermore, pour point testing was done with a LAB 1300 ST (Linetronic Technologies, Switzerland). The heating value of the biodiesel was measured using an automatic calorimeter, IKA C2000, China. Acid number and iodine value were measured with an ECH 7000 Titrator Type TAN/TBN Titrator (ECH Germany). The Flashpoint of WCONOME biodiesel was tested using a PMA 5 Pensky Martens flash point tester (Anton Paar, Austria), and the Cetane number was measured with a Koehler (K88600).

2.4. Experimental arrangement

Experimental was conducted on a fire pipe boiler at the steam Power Generation System Laboratory at the Faculty Technic of the Universitas Sumatera Utara, which typically uses kerosene as fuel. In this study, the fuel consumption rate and exhaust gas emissions were compared between biodiesel blends of WCONOME (B20, B30, B40, B50, B60, and B70) and commercial biodiesel from palm oil (POME30). The details for

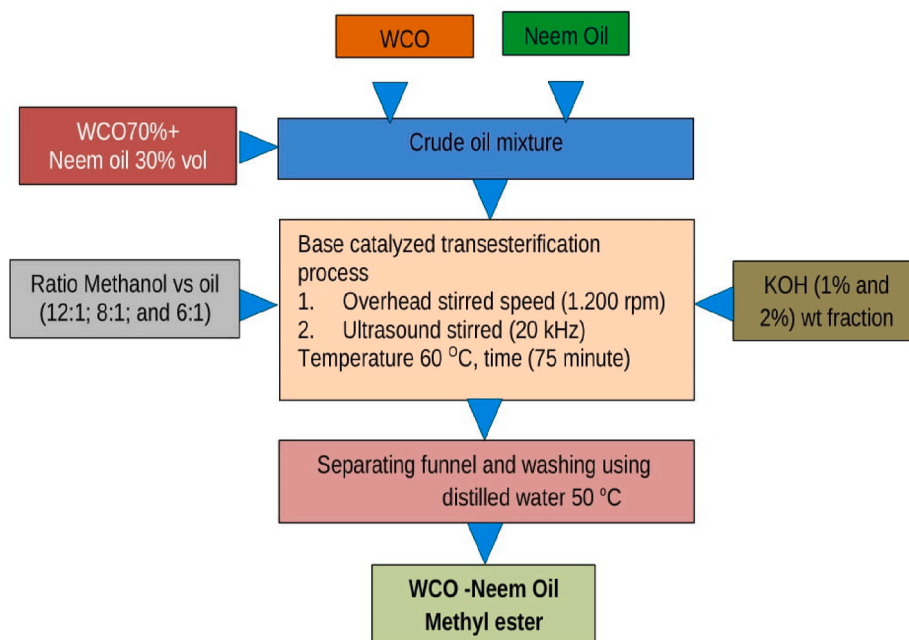


Fig. 2. Flowchart illustrating the transesterification process for WCO-Neem oil mixed oils using both overhead stirring and ultrasonic agitation.

Table 5

Apparatus and testing methods for physicochemical properties.

Property	Equipment	Standard method
Kinematic viscosity at 40 °C	SVM 3000 viscometer cold properties (Anton Paar, Austria)	ASTM D455
Density at 15 °C	SVM 3000 viscometer cold properties (Anton Paar, Austria)	ASTM D455
Pour point	LAB 1300 ST Linetronic Technologies, Switzerland	ASTM D2500
Heating value	Automatic calorimeter, IKA C2000, China	ASTM D4809
Acid number and iodine value	ECH 7000 Titrator Type TAN/TBN Titrator (ECH Germany)	ASTM D664
Flash point	PMA 5 Pensky Martens flash point tester (Anton Paar, Austria)	ASTM D93
Oxidation stability at 110 °C	rapidOxy 100 fuel (oxidation stability tester (Anton Paar, Germany)	ASTM 7525
FTIR	BRUKER-TENSOR 27	ASTM D7371-14
Cetane number	Koehler (K88600)	ASTMD613
GC-MS	Shimadzu Type QP2010 Plus	ASTM6751

each of these fuels can be found in Table 6. Furthermore, the fuel was placed in a tank positioned higher than the boiler to allow the fuel to flow by gravity into the burner. A stopwatch was used to measure the time taken for biodiesel consumption. Fig. 3 presents a schematic representation of the experimental setup of an emission fire tube boiler.

2.5. Experimental setup

The specifications of the fire-tube boiler used in this study are

Table 6

Specification of Fire tube boiler.

Type	Fire tube boiler
Merk	Johnson Boiler
Model/Seri	VRC-150B/V11-522B
Production	1999
steam capacity	150 kg/h
max vapour pressure	10 kg/h

tabulated in Table 6. In this study, a fire-tube boiler equipped with 2 burners, where burner 1 produced saturated steam and burner 2 produced superheated steam, which was used to drive a steam turbine coupled with a generator that generated 1 kW of power. The treated feedwater was directed to the preheater before being fed into boiler 1. Next, steam at a temperature of 120 °C and a pressure of 2 bar produced from boiler 1 was pumped into boiler 2, where it was further heated to produce superheated steam at a temperature of 170 °C and a pressure of 8 bar. To condense the turbine exhaust steam, a condenser was used, and the remaining hot water was reused as feedwater (Fig. 4). A stopwatch was used to measure the fuel consumption in the fire tube boiler. A gas analyzer was used to measure the emissions produced during the fuel combustion process (MET 6.1 merk MAHA).

3. Result and discussion

3.1. Yield of biodiesel WCONOME

Fig. 5 displays the reaction results between oil and methanol with various ratios (12: 1, 8:1, and 6:1), as well as variations in mixing methods (Ultrasound and overhead stirrer) and catalyst concentrations (1 % and 2 %). In general, the highest yield is achieved at a ratio of 12:1, particularly with the use of the Ultrasound method and 1 % catalyst, which is 98.70 %. This result is similar to the one obtained by Pham and Van Nguyen [65], where a biodiesel yield of 98.90 % was achieved using an ultrasound stirrer, while the conventional method yielded 92.73 %. However, as the methanol-to-oil ratio increases, the yield tends to decrease for all combinations of methods and catalyst concentrations, with the Overhead method at 2 % concentration showing more stable results at higher ratios. Hsiao et al. [38] mention that in the biodiesel production from WCO using ultrasound stirring, increasing the molar ratio of methanol to oil in the transesterification process directly also increases the biodiesel yield. In addition to increasing the biodiesel yield, increasing the methanol-to-oil ratio also results in a decrease in the acid value of the produced biodiesel [38]. Similar to the results reported by Abulizi et al. [49], the yield value using ultrasound is higher compared to the conventional method. Topare et al. [66] compared the biodiesel yield from WCO soybean oil using a heterogeneous catalyst (Al₂O₃) with different stirrers (conventional and ultrasound). The

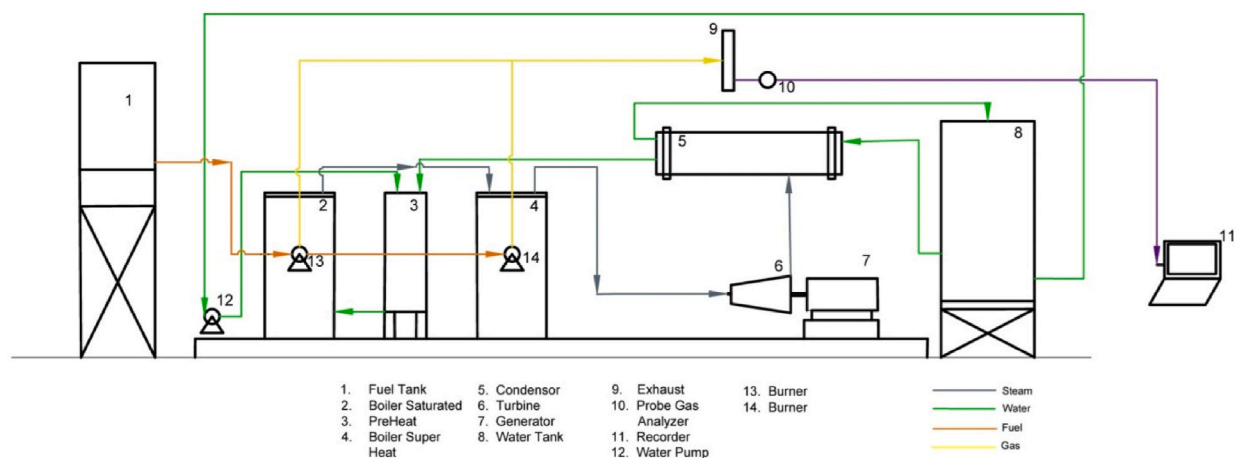


Fig. 3. Schematic of Fire tube boiler.

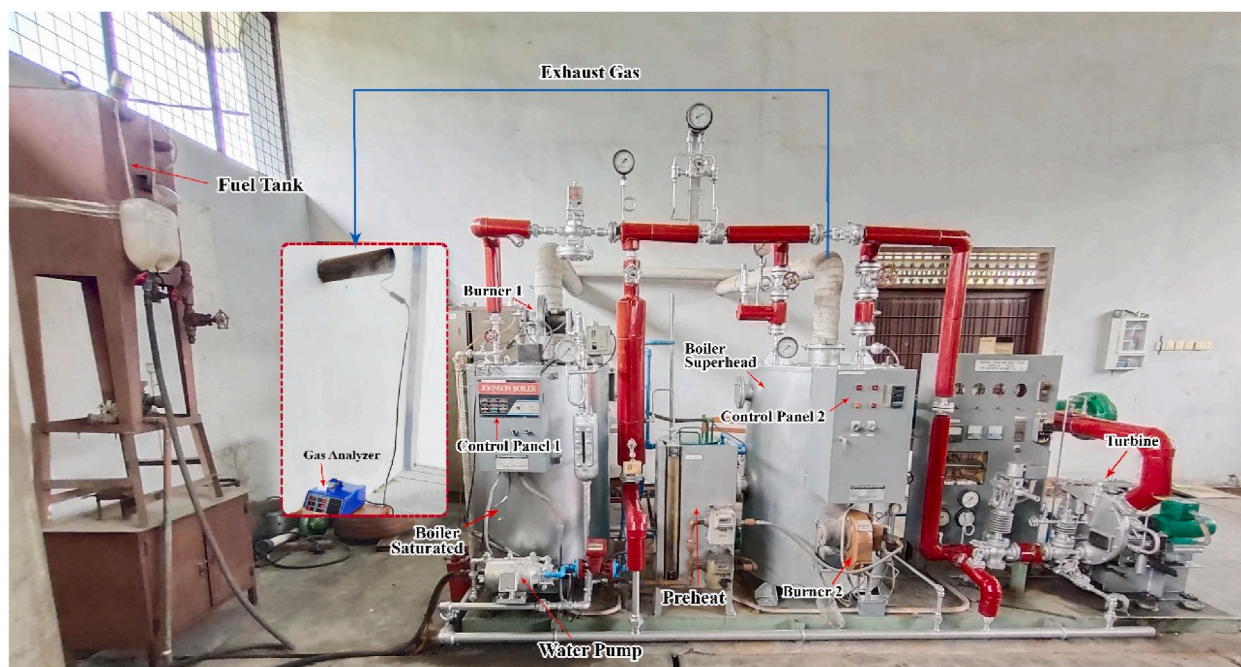


Fig. 4. Fire tube boiler.

research results showed that ultrasound stirring produced a yield of 95 %, while conventional stirring produced 88 %.

The transesterification reaction between vegetable oil and alcohol (e. g., methanol) does not always proceed perfectly. In addition to biodiesel (fatty acid methyl ester, FAME), the transesterification process also produces glycerol as a byproduct. Vegetable oil with high free fatty acid (FFA) content or contamination can lead to soap formation, reducing the efficiency of biodiesel production. Factors such as temperature, reaction time, catalyst amount, and the molar ratio of alcohol to oil affect the conversion yield. Suherman et al. [22] stated that excess methanol causes foam formation and increases the solubility of glycerol in esters, as some glycerides may not react during transesterification. Furthermore, Asl Asl et al. [67] mention that excess methanol also causes biodiesel to shift to the aqueous phase during washing, reducing the final biodiesel yield. In addition, the separation process between glycerol and alcohol becomes more difficult due to the excess methanol.

3.2. Physicochemical properties of biodiesel

3.2.1. Kinematic viscosity

Kinematic viscosity is a crucial property to monitor and regulate since it influences engine start-up characteristics and the performance of the fuel injection system [68]. The kinematic viscosity of the fuel is crucial in determining fuel spray behavior, mixture formation, and the overall combustion process [24]. Table 7 shows the physicochemical properties of WCOME biodiesel, WCONOME, and diesel fuel compared with other research findings. The Kinematic viscosity of WCONOME (4.77 mm²/s) is slightly higher than that of WCOME biodiesel (4.406 mm²/s), but significantly higher than diesel fuel (2.986 mm²/s). Despite being slightly higher than diesel, WCONOME biodiesel still meets the ASTM D6751 standard.

Fig. 6 depicts the kinematic viscosity of samples under four different conditions Overhead (1 % and 2 % catalyst) and Ultrasound (1 % and 2 % catalyst). The results show that the kinematic viscosity is relatively consistent across three of the samples Overhead (1 % and 2 % catalyst), and Ultrasound (2%wt catalyst) with values around 4.7–4.8 mm²/s.

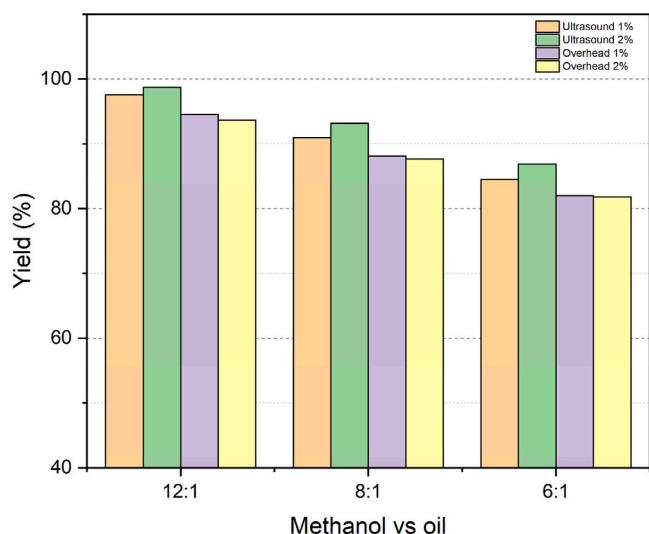


Fig. 5. Comparison of biodiesel yield with different catalyst concentrations.

However, the sample Ultrasound (1%wt) exhibits a noticeably lower kinematic viscosity, approximately $4.5 \text{ mm}^2/\text{s}$, indicating a significant difference compared to the other conditions. This suggests that the Ultrasound (1%wt) may significantly affect the viscosity of biodiesel, reducing it more than the other treatments.

Differences in the type of agitator used in the biodiesel production process, such as mechanical stirring and ultrasound, affect the kinematic viscosity of biodiesel because each method creates different reaction conditions. Mechanical stirring typically produces homogeneous mixing through conventional means, but its energy level may not be sufficient to effectively break down larger molecules. This can result in higher viscosity, especially at higher catalyst concentrations [69].

On the other hand, the use of ultrasound (US) in biodiesel production involves ultrasonic waves that create cavitation, which is the formation of microbubbles within the liquid that then implode, releasing very high local energy [70]. This energy can increase the rate of the transesterification reaction, allowing the breakdown of oil molecules into smaller and more homogeneous esters. Consequently, the kinematic viscosity of biodiesel produced using ultrasound, especially at lower catalyst concentrations (ultrasonic 1 %), may be lower compared to the mechanical stirring method. The differences in mixing efficiency and the energy provided by these two methods are the primary reasons why they affect the kinematic viscosity of biodiesel differently. Overall, the ultrasound stirrer produces a slightly higher kinematic viscosity compared to the conventional method. This result is consistent with the findings of Pham and Van Nguyen [65] where the kinematic viscosity of biodiesel from python fat oil was $4.46 \text{ mm}^2/\text{s}$ using the ultrasound method and

$4.46 \text{ mm}^2/\text{s}$ with the conventional method.

3.2.2. Density of biodiesel

The density of biodiesel plays a crucial role in affecting the fuel injection process and the efficiency of combustion in diesel engines [22]. In the current study, the densities of WCO and WCONO30 are 875 g/cm^3 and 879 g/cm^3 , respectively (Table 7). The density of both types of biodiesel is not significantly different compared to diesel fuel, which has a density of 823 g/cm^3 . This finding is similar to the result obtained by Milano et al. [20], which is 878 g/cm^3 . Furthermore, the results of this study are similar to those of Pham and Van Nguyen [65] where they obtained the biodiesel density from python fat oil using ultrasound and conventional methods at 880.13 kg/m^3 and 881.22 kg/m^3 , respectively.

The density of biodiesel produced using an ultrasonic stirrer (US) is higher compared to that using an overhead stirrer (OH) because an ultrasonic stirrer generates ultrasonic waves that can create cavitation or the formation of microbubbles within the reaction mixture (Fig. 7). This cavitation results in intense turbulence and an increased contact area between the oil, methanol, and catalyst molecules, thereby accelerating the transesterification reaction and enhancing the efficiency of converting oil into biodiesel.

This increased reaction efficiency produces biodiesel with a more uniform molecular structure and a higher conversion of triglycerides into methyl esters, contributing to the increased density. Additionally, the ultrasonic method tends to produce biodiesel with a purer composition, reducing the presence of other compounds that may exist, such as glycerol or unconverted oil residues, which can affect the final density of the biodiesel. In contrast, an overhead stirrer provides more

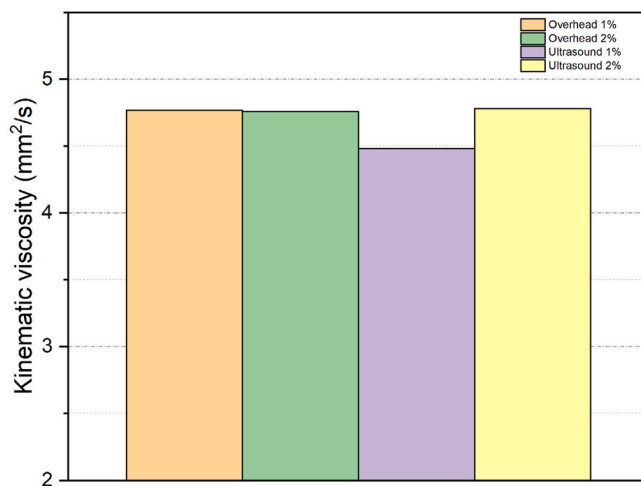


Fig. 6. Kinematic viscosity of overhead and ultrasound stirrer.

Table 7
physicochemical of WCO and mixed.

Properties	Unit	Biodiesel	Diesel	WCOME	WCONOME	POME30	WSME [22]	W70CI30 [20]	WCOMO [16]	Improve
		ASTM D6751								
Kinematic viscosity at 40 °C	mm ² /s	1,9-6.0	2.986	4.498	4.63	5	4.459	5.12	5.08	-2.93 %
Density at 40 °C	kg/m ³	880	823	875	879.5	815	857	878	879	0.51 %
Higher heating value	MJ/kg	-	46.200	40.047	40.94	-	39.952	40.82	39.42	2.23 %
Flash Point	°C	100-170	68.5	143	174	52	172	163.5	78.5	21.67 %
Cetane number	-	Min 47	48	53	56.2	51	-	-	-	6.03 %
Iodine	godiene/100g	-	-	56.3	53.53	-	-	-	-	4.92 %
Oxidation stability	h	Min 3	-	3.3	9.4	35	6.8	18.14	6.5	184.85 %
Pour Point	°C	-15 to-16	6	12	10	18	9	4	-	16.67 %
Cloud Point	°C	-3 to -12	17	25	12	18	21	3	-	52 %

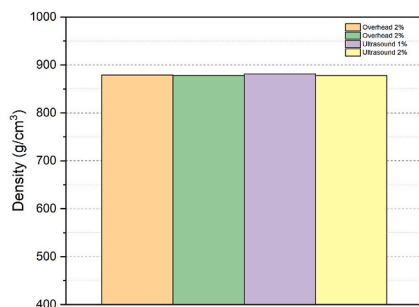


Fig. 7. Comparative density of biodiesel.

conventional mixing with a lower level of agitation, resulting in a slower transesterification reaction that may not be as efficient as an ultrasonic stirrer, leading to biodiesel with a lower density.

3.2.3. The higher heating value (HHV)

The heating value is a vital characteristic of diesel engines in heavy vehicles, as it influences fuel usage and overall efficiency. The higher heating value (HHV) represents the thermal energy released when a unit of fuel is combusted, thereby indicating the fuel's energy content [68]. Table 7 represents the heating values of WCOME and WCONOME biodiesel at 40.07 MJ/kg and 40.7 MJ/kg, respectively, which are significantly lower than diesel fuel (46.20 MJ/kg). Milano et al. [20] reported the calorific value of a WCO-Calophyllum inophyllum (70:30) biodiesel blend to be 40.82 MJ/kg. Furthermore, the calorific value obtained currently is higher compared to the results reported by Bajwa et al. [16], which was 39.42 MJ/kg.

3.2.4. Cetane number

Fig. 8 shows the results of cetane number testing on biodiesel produced using two different mixing methods: overhead stirrer (OH) and Ultrasonic (US), with variations in catalyst concentration of 1 % and 2 %. The test results indicate that biodiesel produced with an overhead stirrer at a 1 % catalyst concentration achieved the highest cetane number, reaching approximately 57.7. When the catalyst concentration was increased to 2 % using the OH stirrer, the cetane number slightly decreased but remained higher compared to the Ultrasonic stirrer. In the Ultrasonic stirrer, the cetane numbers tend to be lower, with a value of around 56 for a 1 % catalyst and further decreasing to approximately 55.7 at a 2 % catalyst concentration. The results obtained are consistent with the findings of Pham and Van Nguyen [65] where the conventional method produced a higher cetane number compared to the ultrasound stirrer method. On the other hand, the cetane number in this study is lower than that reported by Pham and Van Nguyen [65] who obtained a cetane number of 72.46 with the ultrasound stirrer and 73.39 with the conventional stirrer. Overall, the overhead stirring method demonstrated better performance in enhancing the cetane number compared to the Ultrasonic stirrer, and increasing the catalyst concentration does not

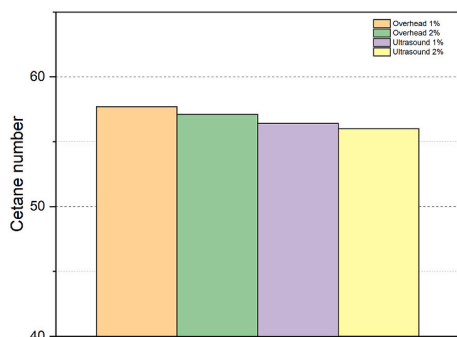


Fig. 8. Cetane number of biodiesel.

necessarily lead to an improvement in the cetane number.

The use of ultrasound in the biodiesel production process can affect the cetane number due to the mechanisms that occur during this process. Ultrasound increases the reaction rate by creating cavitation, which is the formation of small gas bubbles that rapidly explode. This explosion generates high pressure and temperature, which can accelerate chemical reactions, including transesterification used for biodiesel production. However, there are several reasons why the use of ultrasound might lower the cetane number.

Ultrasound can enhance the formation of intermediate compounds that may be undesirable in biodiesel, such as peroxides or other oxygen-containing compounds, which can reduce the cetane number. Further, ultrasound stirred can cause partial degradation of fatty acids into shorter carbon chain compounds or other compounds that have a lower cetane number. The ultrasound can also accelerate the oxidation process, resulting in a higher production of saturated fatty acids. Saturated fatty acids have a lower cetane number compared to unsaturated fatty acids.

This process can also lead to non-uniformity in the molecular size distribution in the produced biodiesel, which ultimately affects the cetane number. These effects do not always occur in all types of biodiesel or under all process conditions. Variables such as ultrasound intensity, the type of vegetable oil used, and other reaction conditions also play an important role in determining the final cetane number. Amran et al. [71] state that biodiesel with a higher cetane number generally results in lower emissions of carbon monoxide (CO) and hydrocarbons (HC) when used in diesel engines.

3.2.5. Flashpoint biodiesel

The flash point is the minimum temperature at which a fuel emits enough vapors to mix with air and ignite [68]. Fig. 9 illustrates the flash point of biodiesel produced using two types of stirrers ultrasound and overhead, with variations in catalyst amounts of 1 % and 2 %. It is observed that the use of an overhead stirrer with a 2 % catalyst produces biodiesel with the highest flash point, approximately 178 °C, while the use of an ultrasound stirrer with a 1 % catalyst yields the lowest flash point, around 172 °C. The higher flash point in overhead stirred 2 % indicates better thermal stability, meaning the biodiesel is safer against spontaneous combustion compared to biodiesel produced under other conditions. This suggests that the type of stirrer and the amount of catalyst significantly influence the physicochemical properties of biodiesel.

The higher flash point of biodiesel using an overhead stirrer compared to an ultrasound stirrer can be attributed to several factors. Overhead stirrers typically provide more consistent and homogeneous

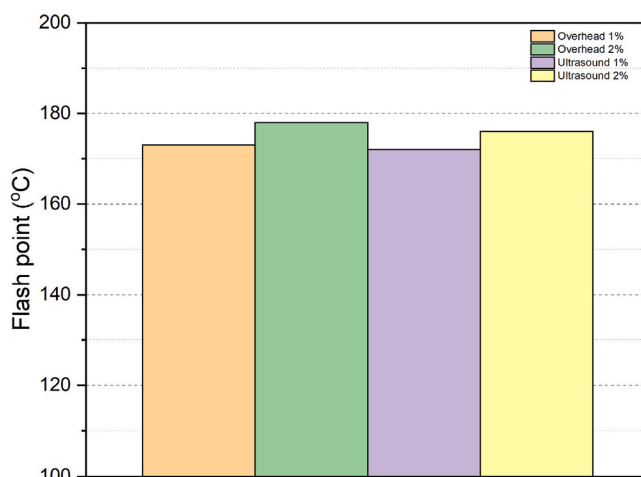


Fig. 9. Flash point of biodiesel WCONOME.

mixing, allowing the transesterification reaction to occur more uniformly and effectively. This results in biodiesel with more stable molecular chains and fewer volatile compounds that could lower the flash point. Furthermore, Ultrasound tends to generate highly localized heat in a short time, which can break down compounds into smaller and more volatile molecules. This can lead to a lower flash point due to the presence of lighter fractions that are more easily combustible. These results are in line with the findings of Pham and Van Nguyen [65], where biodiesel production using an ultrasound stirrer resulted in a lower flash point compared to the conventional stirrer. Pham and Van Nguyen [65] obtained a flash point of 203 °C with the ultrasound stirrer and 206 °C with the conventional stirrer.

3.2.6. Pour point of biodiesel

The pour point is a crucial fuel characteristic for assessing biodiesel's cold flow properties, which determine fuel quality. Biodiesel's poor cold-flow performance is linked to issues like delayed start-up and poor operation in cold climates, primarily due to crystal formation and solid precipitates at low temperatures [28]. It was found the pour point of WCONOME was slightly lower compared to WCOME, 10 °C, and 12 °C. This result is higher than the findings of Milano et al. [20], which was 4 °C. The pour point of biodiesel is influenced by the production method, feedstock, and saturated fatty acid content. Table 7: shows that the total saturated fatty acid content of WCONOME is quite high at 84.774 %. Hence, this is the reason for the relatively higher pour point [19].

3.2.7. Cloud point of biodiesel

The cloud point (CP) is the temperature at which wax crystals begin to appear, causing the fuel to take on a cloudy look as it cools [19]. Table 7 shows the cloud points of WCONOME, WCOME, and POME30. The cloud point of WCONOME was found to be significantly lower compared to WCOME and POME30, 12 °C, 25 °C, and 18 °C respectively. This cloud point is slightly higher compared to reported by Milano et al. [20] at 3 °C. The cloud point is influenced by the saturated fatty acids in the biodiesel, long-chain fatty acids harm the cold flow properties of biodiesel [19].

3.2.8. Analysis of biodiesel using gas chromatography-mass Spectrometry (GC-MS)

The fatty acid esters in biodiesel are categorized as either saturated or unsaturated, with the unsaturated esters being further classified into monounsaturated and polyunsaturated types [19]. The FAME content of the WCOME and WCONOME methyl ester were analyzed using gas chromatography following the EN 14103:2011 standard test method, with the results presented in Table 8. The fatty acid profiles of WCOME and WCONOME show notable variations in the proportion of unsaturated to saturated fatty acids. The overall content of saturated fatty acids of WCONOME (84.774 %) is higher compared to the findings by Milano et al. [20]. (37.01 %) and the research reported that by Bajwa et al. [16] at 10.7 %. Furthermore, the unsaturated fatty acid content in WCONOME biodiesel (15.266 %) is significantly lower compared to the

58.84 % reported by Milano et al. [20]. Next, the palmitic acid in WCONOME biodiesel is higher compared to WCOME, with values of 82.905 % and 49.54 %, respectively. This result is significantly higher compared to the findings of Bajwa et al. [16], which reported 7.85 % in biodiesel blended with WCO and sesame oil. A high saturated fatty acid content in WCONOME will enhance oxidation stability during storage.

The palmitic acid is classified as a saturated fatty acid with a single chain bond (C16:0). Afterward, heptadecanoic acid methyl ester content was found to be 8.01 % in WCOME and decreased to 1.869 % in WCONOME. This reduction is attributed to the addition of Neem oil to the used cooking oil. Furthermore, In WCONOME, the content of unsaturated fatty acids with double bonds, specifically linoleic acid (C18:2), is 12.653 %. This result is slightly higher compared to the findings by Katre [72], which reported 11.66 %.

It was reported that biodiesel produced from a mixture of WCO and other vegetable oils shows a significant content of oleic acid, a mono-unsaturated fatty acid characterized by a single double bond (C18:1). This is in contrast to the result of other research, where in this study lower results were found at 2163 % (Table 8). on the other hand, the content of heptadecanoic acid in WCONOME biodiesel was found to be 1.869 %, which is significantly lower compared to the result found by Ref. [66], which was 8.01 %.

3.2.9. Oxidation stability of biodiesel

The oxidation stability is a physical property that reflects the aging behavior of liquid fuels during transportation and storage [68]. The build-up and condensation of these molecules negatively affect the oxidative stability of biodiesel [73]. Table 7 displays the oxidation stability of WCOME and WCONOME. The oxidation stability of WCOME and WCONOME is 3.6 hours and 9.4 hours, respectively. The addition of neem oil to crude WCO increases oxidation stability by 161 %. This result is significantly higher compared to the study by Bajwa et al. [16], in which oxidation stability reported 6.5 hours for biodiesel produced from a blend of waste cooking oil and sesame oil.

3.2.10. FTIR analysis

The adsorption layer formed during the process can be efficiently analyzed using FTIR (Fourier Transform Infrared) spectroscopy. In this study, FTIR spectra were used to compare WCONO30 crude oil with WCONOME biodiesel. Fig. 10 illustrates the FTIR spectra for WCONO30 crude oil and WCONOME, allowing for a direct comparison between them. The FTIR (Fourier Transform Infrared) spectra provided show two different samples WCONOME (red line) and WCONO (black line). Table 9 provides a reference for the wavenumber, absorption strength, vibration type, and group properties of WCO crude oil and WCONOME. Fig. 10 displays the comparison between WCONO30 crude oil and WCONOME using the FTIR spectrum. The spectra cover a range of wavenumbers from 4000 cm⁻¹–500 cm⁻¹, which is typical for identifying functional groups in organic compounds (Fig. 10)

The spectra revealed absorption peaks at 2851 cm⁻¹ and 2923 cm⁻¹, indicating the presence of a methyl group. These peaks are commonly

Table 8

Composition of WCOME, and WCONO30.

FAME (w/w) %	Carbon chain	WCOME ^a	WCME [72]	WCONOME ^b	WSME [22]	W70CI30 [20]	WCOSO [16]	25-WFME [21]
Caprylic	C8:0	–	25	–	–	–	–	0.01
Lauric	C12:0	–	3.2	–	–	–	–	0.36
Myristic	C14:0	–	1.73	–	0.60	0.64	–	0.03
Palmitic	C16:0	49.54	21.13	82.905	51.08	28.97	7.85	13.55
Palmitoleic	C16:1	–	0.91	–	–	–	0.6	–
Heptadecanoic acid	C17:0	–	8.01	1.869	–	–	–	–
Stearic	C18:0	5.55	3.43	–	4.90	7.40	2.85	2.19
Oleic	C18:1	38.16	21.01	2.613	36.25	44.15	46.94	57.33
Linoleic	C18:2	–	11.77	12.653	–	14.11	34.66	20.47
Linolenic	C18:3	6.75	–	–	7.18	0.58	4.33	5.29
Eicosanoic	C20:0	–	2	–	–	–	–	0.78
Heneicosanoic	C21:0	–	1.79	–	–	–	–	–

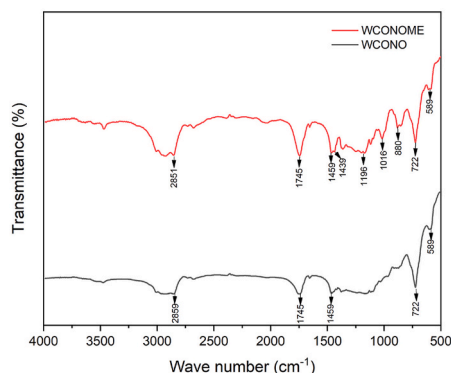


Fig. 10. Comparison of functional groups in FTIR spectra of WCONOME and WCONO.

Table 9

FTIR spectra of crude WCONO30 oil and WCONOME biodiesel.

Wavenumber (cm ⁻¹)	Group attribution	Vibration type	Absorption intensity
2851	-CH ₂	Symmetric stretching vibration	strong
1745	-C=O	Stretching	strong
1459	-CH ₂	Shear type vibration	Weak
1439	-CH ₃	Shear type vibration	Middling
1196	C-O-C	Anti-symmetric stretching vibration	Middling
1016	C-O-C	Anti-symmetric stretching vibration	Middling
722	-CH ₂	Plane rocking vibration	Weak

associated with the C-H stretching vibrations in aliphatic chains, specifically for -CH₂ and -CH₃ groups. The peaks are present in both samples, indicating the presence of long carbon chains in both WCONOME (2851) and WCONO30 (2859). Suherman et al. [22] reported findings that are consistent with this study, identifying a strong -CH₂ symmetric stretching vibration at 2853 cm⁻¹.

Fig. 10 shows is stretching peak detected at 1745 cm⁻¹ in sample WCONOME. This peak corresponds to the C=O stretching vibration, typical of ester functional groups. The presence of this peak in both spectra suggests that both samples contain ester linkages, which are characteristic of biodiesel. This result is similar to the one obtained by Milano et al. [74] which is 1741 cm⁻¹. Mustafa et al. [75] found the same peak between crude oil WCO (1744 cm⁻¹) and FAME (1742 cm⁻¹), these results are similar to the research results obtained.

The peaks at 1459 cm⁻¹ and 1377 cm⁻¹ in the biodiesel spectrum suggest the presence of asymmetric stretching of CH₃, a feature absent in the refined oil spectrum. These peaks are generally attributed to the bending vibrations of -CH₂ and -CH₃ groups. They are present in both samples, indicating aliphatic chain structures in both. In this work, it was found a peak at 1439 cm⁻¹, indicating asymmetric CH₃ stretching. This outcome is comparable to the findings reported by Kodgire et al. [24], which showed a peak at 1436 cm⁻¹. Next, the peak of 1198 cm⁻¹ indicates the presence of C-O stretching in esters, suggesting the presence of ester compounds in the biodiesel. The peak 1016 cm⁻¹ in WCONOME (red line) is often associated with the C-O-C stretching vibrations in esters, this peak confirms the presence of ester groups.

Fig. 10 shows the peak 880 cm⁻¹, 722 cm⁻¹, and 598 cm⁻¹ (red line) in sample WCONOME. These peaks can be related to out-of-plane bending vibrations of -CH groups in aromatic compounds or the bending vibrations of -C-H in alkanes. Their presence suggests certain structural features in the molecules of the biodiesel.

The WCONOME sample (red line) shows more pronounced peaks at various wavenumbers, particularly in the regions corresponding to ester functional groups (1745 cm⁻¹ and 1198 cm⁻¹). This suggests that

WCONOME might have undergone more complete esterification, resulting in a higher concentration of methyl esters compared to WCONO30. Furthermore, WCONO30 (black line) has weaker signals, especially around the carbonyl stretching region (1745 cm⁻¹), which could indicate lower ester content or the presence of unreacted oils or fatty acids.

The FTIR analysis suggests that WCONOME is likely a more refined biodiesel with a higher concentration of ester groups compared to crude oil WCONO30. WCONOME shows more distinct absorption, particularly in regions related to esters, indicating that it is likely richer in ester content. The presence of characteristic peaks for esters and aliphatic chains in both samples indicates that WCONOME is biodiesel.

3.2.11. Fuel flow rate

Fig. 11 depicts a comparison of fuel flow rate in kg/h for various types of biodiesel, including POME30, B20, B30, B40, B50, B60, and B70. It is observed that the fuel flow rate increases with the rising percentage of biodiesel in the mixture. The POME30 has the lowest fuel flow rate, while B70 has the highest, indicating that a higher biodiesel content generally requires a greater flow rate to produce the same energy as mixtures with a lower biodiesel content. This could be attributed to the increased viscosity and density in biodiesel blends with a higher biodiesel content. The increased density of methyl esters resulted in greater fuel mass flow rates compared to petrodiesel [76]. On the other hand, POME30 has a higher calorific value compared to WCONO30 biodiesel, resulting in a lower fuel consumption rate tabulated in Table 7.

3.3. Exhaust gas emissions

3.3.1. CO emission

Fig. 12 depicts the recorded carbon monoxide (CO) emissions for different biodiesel blends, varying from B20 % to B70 %, along with POME30. The study found that the POME30 showed the highest emissions at around 0.85 %, indicating that it produces the most CO compared to biodiesel WCONOME and blends. As the biodiesel content increases from B20 to B50, there is a noticeable reduction in CO emissions, dropping from approximately 0.55 % in B20 to around 0.25 % in B50. However, from B30 to B70, the reduction in CO emissions begins to level off, with emissions ranging between 0.3 % and 0.35 %. This suggests that while higher biodiesel content reduces CO emissions, the effect diminishes after a certain point. Overall, the chart highlights the environmental benefits of using biodiesel blends over POME30, with lower CO emissions associated with higher biodiesel content. A similar trend was found by Ref. [53], where increasing the biodiesel content in

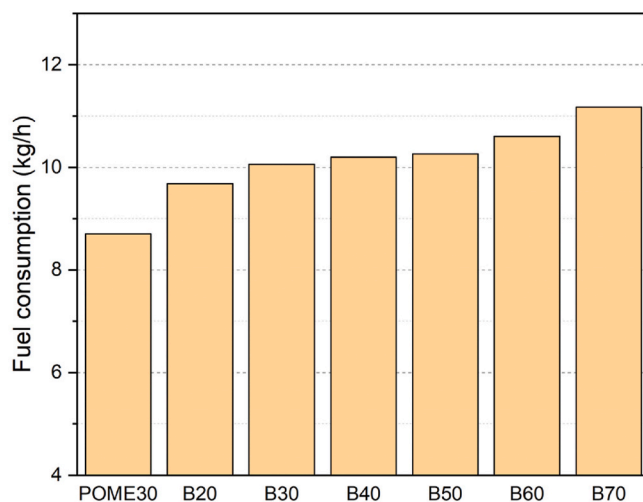


Fig. 11. Fuel flow rate of Boiler.

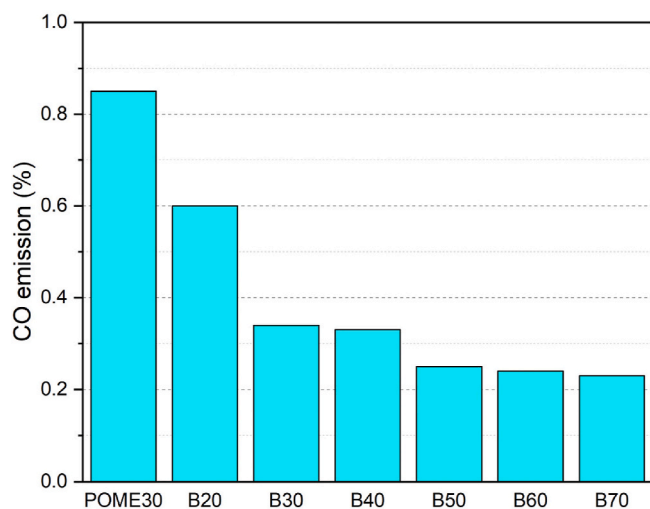


Fig. 12. CO emission of Boiler.

diesel fuel reduced CO exhaust emissions in boilers. According to Bahadorizadeh et al. [2], the reduced CO emissions from the differences between biodiesel and pure diesel are due to its higher oxygen content and lower carbon content. Bazoooyar et al. [76] reported that at low fuel pressures, the CO emissions produced by biodiesel are higher compared to diesel.

3.3.2. CO₂ Emission

CO₂ is a significant emission that needs to be managed in the atmosphere. The accumulation of this gas in the environment leads to global warming and climate change as a result of its greenhouse effect [55]. Fig. 13 depicts the percentage of CO₂ emissions associated with different fuel blends, ranging from POME30 to various biodiesel mixtures (B20 to B70). In this study, the POME30 fuel exhibits the highest CO₂ emission at approximately 16 %. As the biodiesel content in the fuel increases (from B20 to B70), a noticeable decline in CO₂ emissions is observed. B20 and B30 have similar emission levels, slightly below POME30, while B40, B50, B60, and B70 progressively show lower emissions. The lowest CO₂ emission is recorded for the B70 blend, indicating a trend that higher biodiesel content results in reduced CO₂ emissions. This suggests that biodiesel blends, particularly with higher concentrations, are more environmentally friendly in terms of CO₂ output. Bahadorizadeh et al. [2] state that the elevated CO₂ emissions from biodiesel samples In comparison to diesel, this is attributed to the

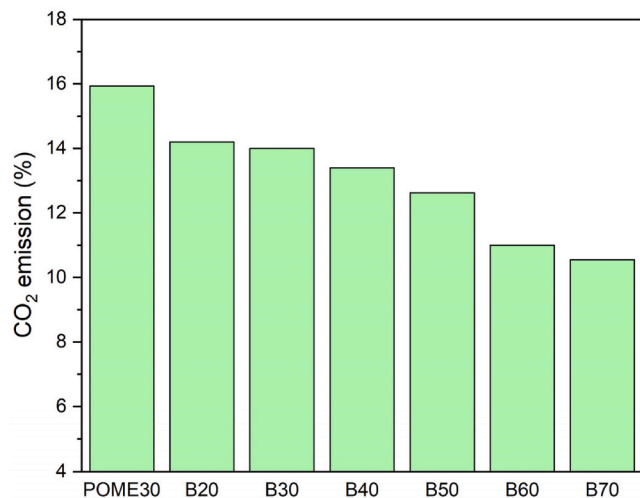


Fig. 13. Impact of biodiesel blending on CO₂ emissions.

higher oxygen content in biodiesel, which enhances combustion efficiency and results in increased CO₂ production. According to San José et al. [77], fossil fuel CO₂ emissions are reduced when biodiesel is blended with diesel.

3.3.3. Oxygen concentration

Fig. 14 shows the oxygen concentration in the exhaust for various fuel blends, ranging from POME30 to B70. The data shows a steady increase in oxygen concentration as the proportion of biodiesel in the blend increases. The result indicates that the POME30 exhibits the lowest oxygen concentration at around 0.7 %. As the biodiesel content rises to B20, B30, and B40, the oxygen concentration remains relatively stable, fluctuating around 0.8 %. However, a noticeable increase occurs at B50 and B60, with oxygen concentration reaching approximately 0.9 %. The most significant rise is observed in the B70 blend, where oxygen concentration peaks at 1.6 %, indicating that higher biodiesel content in the fuel blend leads to an increase in oxygen concentration. These results are lower compared to the findings of Lin and Wu [54], which are around 3 %, where at full load, the oxygen concentration in the exhaust gas is approximately 2%–3%.

3.3.4. Hydrocarbon emission

Fig. 15 shows the hydrocarbon emissions (in ppm) associated with different fuel blends, ranging from POME30 to B70. The data reveals that POME30, a conventional diesel fuel, produces the highest hydrocarbon emissions, peaking at over 400 ppm. As the biodiesel content increases from B20 to B70, there is a noticeable decline in hydrocarbon emissions. A similar trend was found in the study by Ref. [53], where increasing the biodiesel ratio in diesel fuel reduced HC emissions from boiler exhaust gases. Specifically, B20 shows a significant reduction compared to POME30, and further decreases are observed with each subsequent blend, with B70 displaying the lowest emissions, around 200 ppm. This trend suggests that higher biodiesel content in fuel blends correlates with reduced hydrocarbon emissions, indicating the environmental benefits of using biodiesel over POME30. This result is higher compared to the findings of [58], who used palm oil biodiesel in a B25 blend, which amounted to 16 ppm.

3.3.5. Energy usage analysis

Based on the measurement results, the power consumption for biodiesel production with different types of stirrers (overhead and ultrasound) is presented in Table 10. The total energy required for biodiesel production using the overhead stirrer method is 0.358 Wh, while biodiesel production with ultrasound stirring requires a total energy of 0.841 Wh, assuming that the transesterification process for both

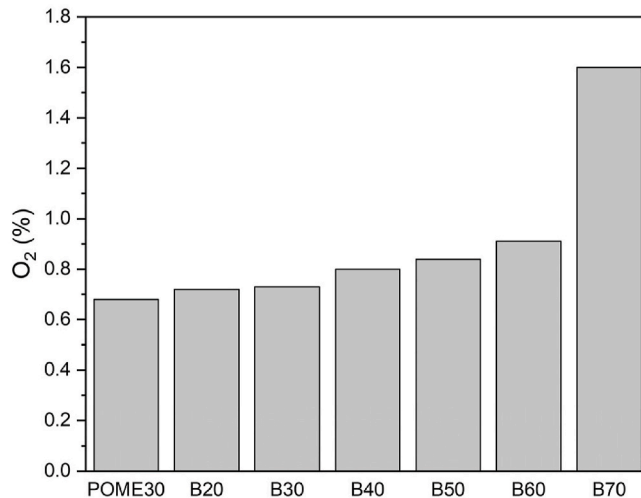


Fig. 14. Oxygen profile for various fuel blends.

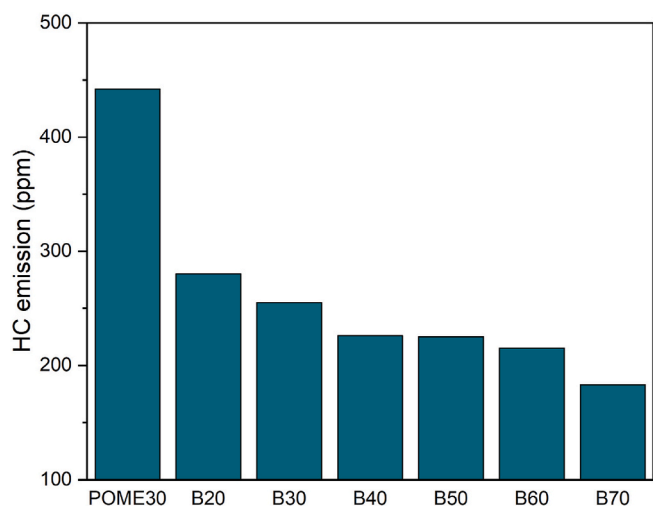


Fig. 15. Hydrocarbon emissions for different diesel and biodiesel fuel types.

Table 10

Comparison of energy consumption with different types of stirrers (overhead and ultrasound stirrer).

Methods	Energy consumption (Wh)		Total energy (Wh)
	pretreatment	Transesterification	
Overhead Stirred	0.244	0.118	0.358
Ultrasound	0.244	0.597	0.841

methods takes 90 minutes.

3.3.6. By-products of biodiesel production

Biodiesel, a major renewable energy source produced in significant quantities globally, generates various residues and by-products during its production process, which brings about economic and environmental challenges [78]. Additional products such as oil cake or meal, methanol, raw glycerol, and biodiesel wash water [79]. Glycerol is the primary by-product of biodiesel transesterification. However, the glycerol obtained from biodiesel production is of low quality and has a low market value [78]. Glycerol can be converted into polyglycerol polyester polyol, which can be applied in thermoplastic polyurethane [80]. The substantial amount of residues pose disposal and environmental challenges, as these wastewaters contain a high organic load, preventing their direct release into sewage systems [78]. Glycerol by-products from biodiesel production plants can be utilized as polyhydroxyalkanoates (PHA) [81]. Biological solid residues are typically used in composting or animal feed; however, these materials could enhance the profitability of the biodiesel industry if repurposed as substrates for producing chemical compounds or energy [78].

4. Conclusions

This research presents, biodiesel production from WCO-neem oil mixed using the pilot scale with a capacity of 25 L. The main finding of this study is to observe the effect of stirrer types on the physicochemical properties of WCONOME biodiesel. Besides, the exhaust gas emission characteristics of the fire tube boiler for WCONOME (B20 to B70) and biodiesel commercial (POME30) were thoroughly investigated. It was found that additional neem oil in WCO for increased saturated acid in WCONOME was created to improve oxidative stability and the cold flow properties of the biodiesel, such as (pour point, flash point, and cloud point). Through gas chromatography testing, the saturated fatty acids of WCONOME were found to be 84.774 %, and the unsaturated fatty acid content in WCONOME biodiesel was 15.266 %. In general, the fuel

consumption of POME30 is the lowest compared to other blends when applied to a fire-tube boiler. Furthermore, the exhaust gas emissions produced by commercial biodiesel (POME30) are the highest compared to the other test samples. Moreover, the evaluation of the physicochemical properties of WCONOME biodiesel using both agitation methods (Ultrasound and overhead) has largely met international ASTM D6751 standards, except for the pour point and cloud point. In conclusion, WCONOME is highly feasible for use as fuel in small-scale boilers due to its low exhaust gas emissions. An economic feasibility study on the use of WCONOME is necessary for the future.

Nomenclatures

ASTM	American Society for Testing and Materials
BTE	Brake Thermal Efficiency
BSFC	Brake-Specific Fuel Consumption
B0	Diesel Fuel
B20	Biodiesel of WCO-Neem Oil and Mixed 20 % diesel
B30	Biodiesel of WCO-Neem Oil and Mixed 30 % diesel
B40	Biodiesel of WCO-Neem Oil and Mixed 40 % diesel
B50	Biodiesel of WCO-Neem Oil and Mixed 50 % diesel
B60	Biodiesel of WCO-Neem Oil and Mixed 60 % diesel
B70	Biodiesel of WCO-Neem Oil and Mixed 70 % diesel
CP	Cloud Point
CN	Cetane Number
EN	European standard
EGT	Exhaust Gas Temperature
FAME	Fatty acid Methyl Ester
FP	Flash Point
HHV	High Heating Value of biodiesel
NO	Neem Oil crude oil
OH	Overhead Stirred
OS	Oxidation Stability
PP	Pour Point
POME30	Biodiesel of Palm Oil Methyl ester + 30 %
SO	Stability Oxidation
US	Ultrasound Stirred
WCO	Waste cooking oil crude oil
WCONO30	Waste cooking oil-30%Neem Oil and mixed crude oil
WCOME	Waste Cooking Oil methyl ester
WCONOME	Waste Cooking Oil-Neem oil methyl ester

CRediT authorship contribution statement

Suherman: Writing – review & editing, Methodology, Conceptualization, Writing – review & editing, Methodology, Conceptualization.
Ilmi: Writing – original draft, Project administration, Formal analysis.
M. Sabri: Formal analysis. **Edo Fransisko Ginting:** Resources, Investigation. **Josua Jose Silalahi:** Visualization, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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