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Assessment of waste cooking oil-based biodiesel blend: Properties, performance and optimal blend ratio

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ABSTRACT

Biodiesel has gained a lot of attention recently as a clean alternative to traditional diesel. However, the scarcity of feedstock is the primary reason for concern regarding its manufacturing cost. Due to the substantial expense of raw materials compared to fossil fuels, the cost of biodiesel produced via transesterification from virgin vegetable oil is greater. Waste Cooking Oil (WCO) has been utilized as a feedstock recently in an effort to reduce the price of biodiesel. NaOH is typically utilized as an alkaline catalyst due to its cheaper cost and faster pace of reaction. After producing biofuels and characterizing them, performance was assessed by blending them with diesel. Extensive studies of fuel analysis were conducted on a range of mixtures starting from B5 to B30 with a 5% change in blend of bio-fuel to diesel. From the study, it was found that the B30 blend has the maximum deviation of properties when compared to diesel fuel. The kinematic viscosity of theee B30 fuel was 47% higher than the diesel. The diesel has a 3.5% higher calorific value compared to B30, which will affect the specific fuel consumption of the engine. The flashpoint of the B30 blend was 24% higher than the diesel, which leads to easy fuel transport. The density of both diesel and B30 blends exhibits very little change of about 0.7%. Comparing the blend with diesel, it was observed that the characteristics of blends up to B20 are much closer to diesel fuel. Beyond B20, the properties deviated rapidly, which will affect the performance and the emission characteristics of the engine.

Keywords: biodiesel, waste cooking oil, alternative fuel.

INTRODUCTION

The utilization of biomass resources for biofuel production has gained global attention due to climate change concerns and rising oil prices. Researchers are increasingly focusing on renewable technologies to address these challenges (Aransiola *et al.*, 2012; Hinduja *et al.*, 2024). Biofuels, derived from biomass, present a sustainable alternative to traditional fuels, being non-toxic. biodegradable, and economically feasible, thereby helping to reduce the reliance on fossil fuels. Their abundance further supports environmental sustainability and energy security. As a sustainable energy source, biofuels play a crucial role in mitigating global warming and promoting responsible energy (Pugh *et al.*, 2011).

Numerous factors, including temperature, catalyst type, chemical selection, and reaction time. are critically considered in biofuel production. Optimizing these conditions maximizes biofuel output while minimizing environmental impact, contributing to a more sustainable energy future (Puri *et al.*, 2012). However, the transition to renewable energy sources is imperative due to the negative effects of fossil fuel consumption on both people and the environment, exacerbated by industrialization, population growth, as well as technological advancements(Malik *et al.*, 2024) Promoting biofuels also requires ensuring raw material availability, sustainable manufacturing, and effective marketing strategies, as different countries possess varying resources and policy frameworks (Cadenas and Cabezudo, 1998).

As easily accessible crude oil reserves dwindle and energy consumption increases, a severe energy shortage looms on the horizon. Current trends indicate that fossil fuels alone will not meet global energy demands in the near future (Dhawane *et al.*, 2018). Diesel fuel, commonly used in transportation, burns incompletely, releasing various pollutants. While diesel engines emit less carbon monoxide than gasoline engines, they produce higher levels of nitrogen oxides and aldehydes, which can irritate the respiratory system. Diesel exhaust particles (DEPs) significantly contribute to air pollution in urban areas, with submicron soot particles mediating several adverse health effects(Long and Carlsten, 2022). The depletion of petroleum reserves and growing environmental awareness have led to an increased focus on renewable energy sources. Among these, vegetable-based oils are key candidates for biodiesel production, serving as a renewable substitute for diesel fuel (Benny *et al.*, 2024; Lin and Wu, 2022; Ülgen *et al.*, 2025). Biodiesel can be used alone or blended with petroleum-derived diesel. It is biodegradable, non-toxic, and renewable, offering significant advantages over traditional diesel fuels, including a higher cetane number and lower emissions of carbon monoxide, hydrocarbons, and particulates (Graboski and McCormick, 1998).

The development of biodiesel as a diesel substitute has garnered significant interest. Due to its positive environmental impacts, biodiesel derived from renewable biomass, including plant and animal fats, has gained popularity (Demirbaş, 2003). The properties of biodiesel are similar to that of diesel, which does not need any modifications in the engine, as presented in Table 1 (Demirbas, 2009). Used cooking oils, categorized as first and second used cooking oils, are particularly promising. First-used cooking oil, generated by fast-food establishments, is the waste from fresh vegetable oil, while second used cooking oil is sourced from food vendors and is often discarded without treatment (Kawentar and Budiman, 2013). Converting this leftover oil into biodiesel offers both ecological and economic benefits, as used cooking oil is a cheaper raw material that reduces waste disposal costs (Demirbaş, 2003) Recent studies indicate that utilizing used cooking oil can cut biodiesel production costs by nearly half (Escobar *et al.*, 2009). With an estimated 15 million tons of used cooking oil disposed of annually worldwide, exploring this low-cost raw material could significantly help in meeting the global biodiesel demand (Das *et al.*, 2024; Lee *et al.*, 2014).

Economic aspects

One potential growth booster that could help in resolving a nation's economic issues and reducing its reliance on fossil fuel is biodiesel (Avinash and Murugesan, 2017). The elimination of poverty, the advancement of agriculture, the generation of renewable energy, economic expansion, environmental preservation, as well as reduction of greenhouse gas emissions are all associated with biofuel (Hasan *et al.*, 2023; Sakthimurugan *et al.*, 2025). Improving the technology productivity to boost yield, lower capital investment costs, and lowering raw material costs can all help to reduce the cost of producing biodiesel (Gebremariam and Marchetti, 2018). The primary expense of producing biodiesel is oil feedstock, which makes up

Table 1. Properties of biodiesel and diesel (Demirbas, 2009)

Fuel properties	Biodiesel	Diesel
Density at 15 °C/cm^3	0.8834	0.8340
Viscosity at 40 °C, mm^2/s	4.47	2.83
Sulphur content, %	< 0.005	0.034
Carbon content, %	76.1	86.2
Hydrogen, %	11.8	13.8
Oxygen, %	12.1	-
Flash point, °C	178	62
Cetane number	56	47
Net calories value, kJ/kg	37,243	42,588
Cloud point	270–285	258–278

70% of the overall cost. Therefore, using WCO as feedstock can greatly reduce the production cost furthermore, it lowers the cost of waste treatment (Hirkude *et al.*, 2018).

The current biodiesel price in India varies depending on the blend, but more or less it is available between a price range around Rs60–70 per litre. On the other hand, the price of petroleum diesel is around Rs 89–92 per litre. Since waste cooking oil is used as raw material, methanol as alcohol and sodium hydroxide as catalyst, the overall cost of biodiesel is cheaper compared to traditional diesel. By 2033, the biodiesel market in India is projected to grow to a value of approximately US$ 0.69 billion. Nevertheless, it was valued at US$ 0.37 billion in 2024, and CAGR is anticipated to be approximately 7.05% from 2025 to 2033 due to the growing use of sustainable fuels, government programs for renewable energy, and a growing emphasis on lowering carbon emissions in industrial and transportation sector. Techno-Economic Analysis experiments indicated that while biohydrogen (US$9–33/kg) showed a higher minimum selling price, bioethanol and biobutanol were competitive with their current market values (Patel *et al.*, 2025).

The objective of this work was to achieve the transesterification reaction in waste cooking oil (WCO) to produce biofuels and its performance as in engine when blended with diesel in various combinations.

MATERIALS AND METHOD

Oil collection and preparation

The used WCO was collected from the Karnataka, Mysuru. Five litres of canes were distributed to local stores and street vendors, encouraging them to collect leftover waste oil after their daily use. This simple yet impactful strategy not only provided a convenient means for waste oil disposal but also engaged individuals in sustainable practices. The waste cooking oil was procured without any cost. The 70% of total production cost of biodiesel is from raw material, collecting the waste oil at zero cost was economically advantageous. Once filled, the canes were collected from each establishment, ensuring a systematic approach to waste oil collection across the city. The collected oil, a mixture of vegetable and non-vegetable fried items with suspended solids, were filtered using strainers and muslin cloth. This crucial step removes impurities, enhancing the quality of the oil for potential reuse or recycling. The filtered waste oil was then stored in larger containers, awaiting further processing or disposal. By involving local businesses and residents in the collection and management of WCO, the initiative promoted a sense of ownership and responsibility towards environmental conservation.

Transesterification process

The first step in turning 5 litres of WCO into biofuel is to make a catalyst by dissolving 50 grams of sodium hydroxide in 1 litre of methanol. To improve the receptivity of oil, it was heated at 60 °C using a magnetic stirrer. Slowly sodium methoxide was added to the oil and continue stirring (Figure 1). Transesterification process takes one and a half hours to complete by forming two layers, that is methyl ester biofuel and glycerine (Figure 2). Glycerine forms a bottom layer and methyl ester a top layer when the mixture settles after the reaction. Glycerine is removed by the decantation process, where biofuel is transferred into another container. Biofuel was washed with distilled water at 55 °C to remove excess sodium hydroxide, methanol or any water-soluble contaminants and continue the same for three to four times. Lastly, the biofuel was given a final heat treatment to remove any remaining moisture at 90 °C, guaranteeing its purity and fuel efficiency. From 5 litres of WCO, around 4 litres of biofuel were obtained via the transesterification method, which is 80% biofuel yield.

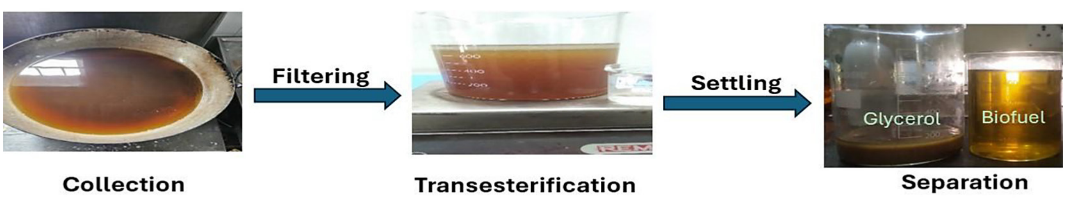

Figure 1. Transesterification process

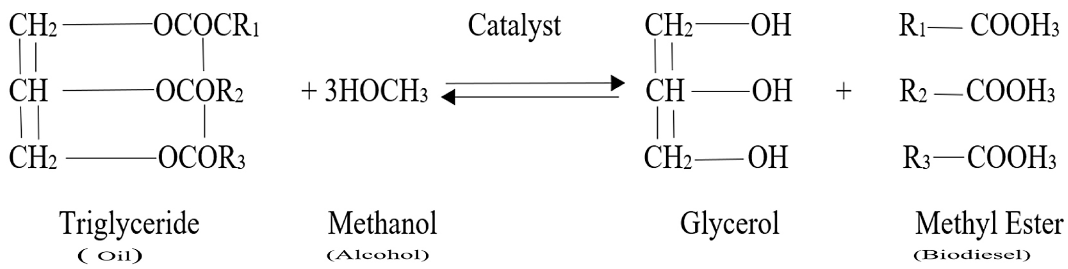

Figure 2. Transesterification reaction

RESULTS AND DISCUSSION

The individual properties of the fuel blend was determined according to ASTM standards.

Oil parameters

The oil is subjected to parameter checking, as presented in Table 2. They are the peroxide value, iodine value, saponification value, acid value.

Biofuel analysis

The biofuel (B100) produced from WCO is checked for the fuel analysis with parameter like gross calorific value, viscosity, water content, density, sulphur content, fire point, flash point, ash content and the values are presented in the Table 3.

Higher heating value (HHV) and gross calorific value (GCV) are equivalent. Higher heating value (HHU) is used for fluid fuels, and GCV is used for solid fuels. It alludes to the warmth of combustion, which occurs when all combustion products reach the temperature of the reactants and condense into water vapour. Since heating value permits the energy content to be combustible, it might be an especially notable feature of diesel engines. Warming value is expressed as net and net calorific value, determined by the degree of water display within the debilitated state. In the case that the water display is dynamic, warming value is GCV. The warming value is referred to as NCV if the water is visible as vapour. From this Gross Calorific Value of biofuel is 10201 kcal/kg. The interior friction or flow resistance of oil is measured by its viscosity. Oil may flow more easily when its temperature rises because its viscosity drops with warmth. The most significant characteristic of biodiesel is its viscosity, which has an impact on how fuel injection machinery functions, especially at low levels of temperature. when the fluidity of the fuel is impacted by an increase in viscosity. High viscosity causes the fuel spray to be less evenly atomized, which in turn causes the fuel injectors to operate less precisely. Following the transesterification process, the viscosity values of waste oil methyl esters drastically drop. Ordinarily, the viscosity of methyl ester was irrelevantly above that of routine diesel combustible at 40 °C. At 40 °C, the viscosity of the biodiesel is 4.25 CST and at 100 °C the viscosity is 1.5 CST(Sivaramakrishnan and Ravikumar, 2011).

Moisture content is the most important parameter in the fuel characterization. Rusting can occur when biodiesel fuels contain water. Water is also an essential component for the development of microorganisms. The gasoline must have a clean look, be devoid of any water, and silt. These things are typically signs of improper handling procedures. Water and silt can clog gasoline filters or reduce their lifespan, which can starve engines of fuel. Furthermore, water can encourage microbial development and drive corrosion (Barua, 2011; Rocha-Meneses *et al.*, 2023). It was discovered that the material in this experiment had no water, its value was < 0.1. In the context of specifications such as IS 1448 Part 40 for biodiesel, it means that the parameter being measured (in this case, water content) is expected to be below 0.1%. It could be any value smaller than 0.1%, including 0%. The water was removed

Table 2. WCO parameters

Sl. no.	Test name	Result
1	Density	0.84 g/ml
2	PH	9.14
3	Colour	Brownish yellow
4	Acid value	1.683 mg KOH/g
5	Saponification value	378.8 mg OH/g
6	Iodine value	25.413 wijs
7	Peroxide value	10 meq/1000 g

Table 3. Biofuel analysis for B100 before the blending with diesel

Test name	Unit	Result
Gross calorific value	kcal/kg	38000
Viscosity at 40 ºC	Cst	4.25
Viscosity at 100 ºC	Cst	1.59
Water content	%	< 0.1
Density at 31 ºC	g/cc	0.8602
Sulphur content	%	0.16
Fire point	ºC	163
Flash point	ºC	179
Ash content	%	0.001

using a rotating evaporator. For water and sediment, the ASTM standard limit was 0.05% by sample volume (Chhetri *et al.*, 2008).

Sulphur has an influence on the environment, human health, and performance, the sulphur level of biodiesel is crucial. Elevated sulphur emissions damage ecosystems and human health by causing air pollution and acid rain. Biodiesel lessens these harmful effects by reducing sulphur concentration, which complies with emission standards and encourages cleaner combustion. Reduced sulphur levels also protect catalytic converters and engine parts, guaranteeing effective engine operation and extending equipment life. According to Indian standard, the sulphur content should be within 15 ppm. In the testing of biofuel in lab method determined percentage was 0.16%. The lowest temperature at which biodiesel fuel will begin to fire (flash) when an ignition source is applied is known as the fuel flash point temperature. Flash point varies in opposition to the volatility of the fuel. For the safe handling and storage of diesel fuel, minimum flash point temperatures are necessary. The lowest temperature at which the sample may burn for five seconds is known as the fire point. When evaluating the fire hazard (the temperature at which fuel can release flammable vapour), these two factors are crucial (Lin and Wu, 2022). The standard value of flash point was in between 100–170 °C.The obtained biofuel flash point value was 163 °C. The standard fire point value is 100–190 °C. The obtained result was 179 °C. These values are a satisfactory result for biofuel. The residue that remains after burning biodiesel is referred to as the ash content of the fuel. Inorganic compounds including metals, salts, and other non-combustible materials make up the majority of this waste. An excessive amount of ash can be harmful, since it can develop engine deposits and perhaps harm engine parts. Because of this, the ash content limitations are usually included in biodiesel regulations in order to guarantee the fuel quality and engine compatibility. Depending on the biodiesel standard or specification being followed, there may be variations in the precise ash content limit. For example, the commonly used ASTM D6751 standard for biodiesel in the US calls for a maximum ash level of 0.01% by weight. The obtained result was 0.001% which is a safe and satisfactory result (Tarigan *et al.*, 2023).

The biofuel produced by cooking oil is compared with the standard works to understand its merits (Table 4). On the basis of their respective Gross Calorific Values (GCV), which are 10079 Kcal/kg, 38000 Kcal/kg and 10201 Kcal/kg, respectively, *Azadirchta excelsa* Oil Methyl Ester (AOME), *Tabebuia rosea* methyl ester (TOME) and Waste Cooking Oil Methyl Ester (WCOME) exhibit a more similar value, because biodiesel has a higher oxygen concentration than diesel, it has a lower caloric value. While the lowest viscosity of *Azadirchta excelsa* seed oil makes it easier to utilize in engines and fuel systems, the recent research on WCO methyl esters value also reveals a closer resemblance to other fuels (Lhawang *et al.*, 2021). *Azadirchta excelsa* Oil Methyl Ester and WCO Methyl Ester have comparable densities, which suggests comparable mass per unit volume. Among the oils, WCO has the lowest sulfur level, meaning it would cause less emissions and corrosion. The highest flash point is found in WCO, which is beneficial for storage and transit safety. When compared to *Tabebuia rosea* seed oil, WCO has the low ash concentration, indicating cleaner combustion (Sirigeri *et al.*, 2022).

Table 4. Comparison between present study with *Tabebuia rosea* methyl ester and *Azadirchta excelsa* methyl ester (Lhawang *et al.*, 2021; Sirigeri *et al.*, 2022)

Sl. no.	Properties	TOME	AOME	Present study (WCOME)
1	Gross calorific value	10079 kcal/kg	10540 kcal/kg	38000 kcal/kg
2	Viscosity at 40 ºC	3.99 Cst	3.465 Cst	4.25 Cst
3	Density	-	0.8635 g/cc	0.8602 g/cc
4	Sulphur content	1.20%	1.66%	0.16%
5	Flash point ℃	170 ºC	156 ºC	179 ºC
6	Ash content	0.02%	-	0.001%

Biodiesel analysis

Biofuel was blended with diesel in various proportions on basis of volume. The characterization of these blends was done and tabulated.

Figure 3 shows comparison of kinematic viscosity for various fuel blends, the least value of kinematic viscosity is observed in diesel and as the percentage of biofuel increase, the kinematic viscosity also increased. The kinematic viscosity of B100 fuel is very high when compared with rest of the blends. The kinematic viscosity of B20 and B30 fuel are 40% and 47% higher than that of the diesel. The blend B5 has 25% higher kinematic viscosity compare to the diesel.

The comparison of calorific value for various fuel blends is shown in Figure 4, The maximum calorific value was observed in diesel, and as the amount of biofuel increased, the calorific value decreased. The B100 fuel has a low calorific value when compared to other blends. The B20 and B30 fuel have a lower calorific value than diesel, by 2.3% and 3.5%, respectively. The B5 blend has a 0.7% lower calorific value than the diesel.

Figure 5 compares the flash and fire points of several fuel blends; diesel has the lowest flash and fire point, and as the amount of biofuel increases, the flash and fire point increase slightly. In comparison to other mixes, B100 fuel has a very high flash and fire point. The blend B5 has the same flash and fire point as the diesel.

Figure 6 shows the density of several fuel mixes; diesel has the lowest density, and as the percentage of biofuel increases, the density rises significantly. In compared to other mixtures, B100 fuel is quite dense. The blend B5 has roughly the same density as diesel.

Biodiesel blends were prepared using cooking oil biofuel with the diesel at various proportionate and the results are presented in Table 5. The B20 biodiesel blend has a kinematic viscosity of approximately 3.96 mm^2/s, greater than conventional diesel (2.83 mm^2/s) but lower than B100 (6.23 mm^3/s). Because of its modest viscosity, which improves atomization and injection, B20 can be used with conventional diesel engines without requiring major modifications. Although it has a little lower calorific value (41.5 MJ/kg) than diesel (42.588 MJ/kg), it nevertheless has a high energy density(Azad *et al.*, 2015). B20 has a higher flash point (69 °C) than diesel (62 °C), which increases handling and storage safety. The density of B20, roughly 840 kg/m^3 allows it to burn and inject fuel similarly to diesel while requiring fewer modifications to engines. All things considered, B20 is a sensible, cleaner fuel choice

Table 5. Characterization results for various fuel blends

Sl. No.	Property	ASTM standard	Fuel type							
			Diesel	B5	B10	B15	B20	B25	B30	B100
1	Kinematic viscosity at 40 °C (mm^2/s)	-	2.83	3.52	3.68	3.81	3.96	4.02	4.18	6.23
2	Calorific value (MJ/kg)	ASTMD4809	42.5	42.2	42	41.9	41.5	41.2	41	38
3	Flash point (°C)	ASTMD93	62	63	64	66	70	73	77	179
4	Fire point (°C)	ASTMD93	72	72	74	75	77	85	92	193
5	Density (kg/m^3)	ASTMD1298	830	832	835	835	840	840	840	895
6	Free Fatty Acid (%)	-		-	-	-	-	-	-	0.285

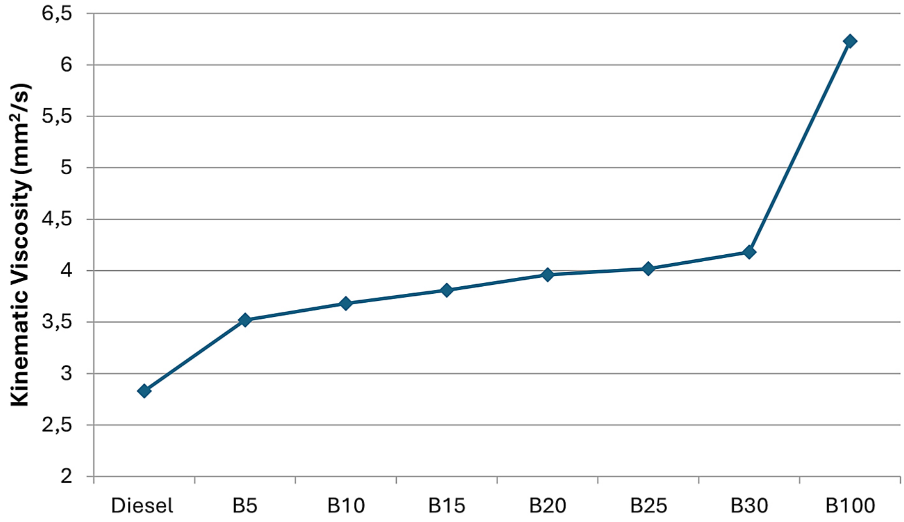

Figure 3. Comparison of kinematic viscosity for various fuel blends

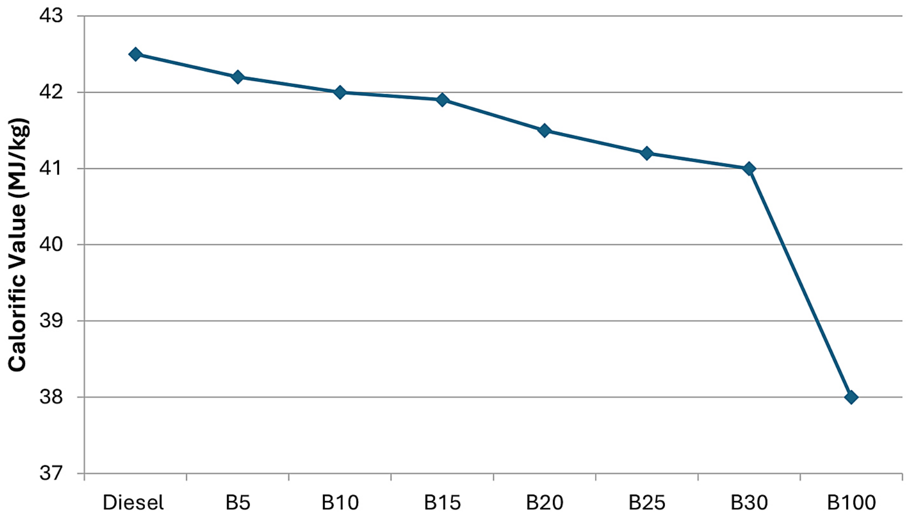

Figure 4. Comparison of calorific value for various fuel blends

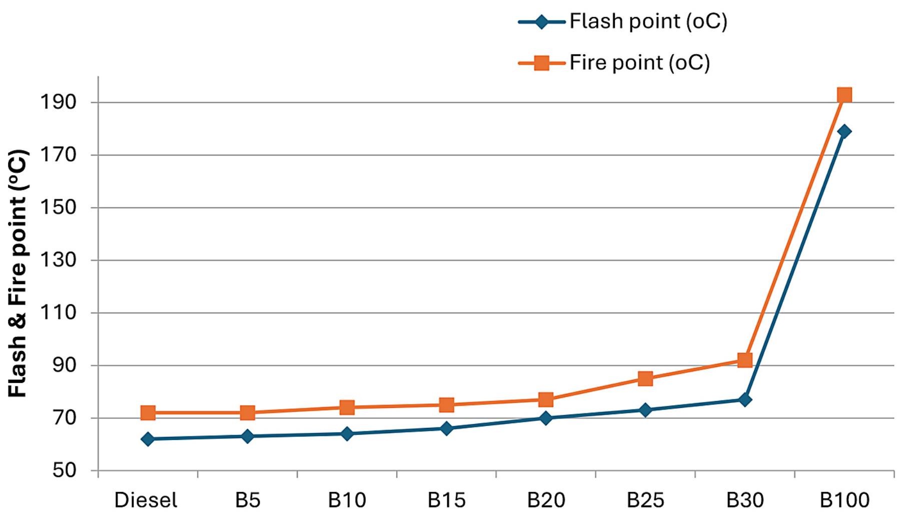

Figure 5. Comparison of flash & fire point for various fuel blends

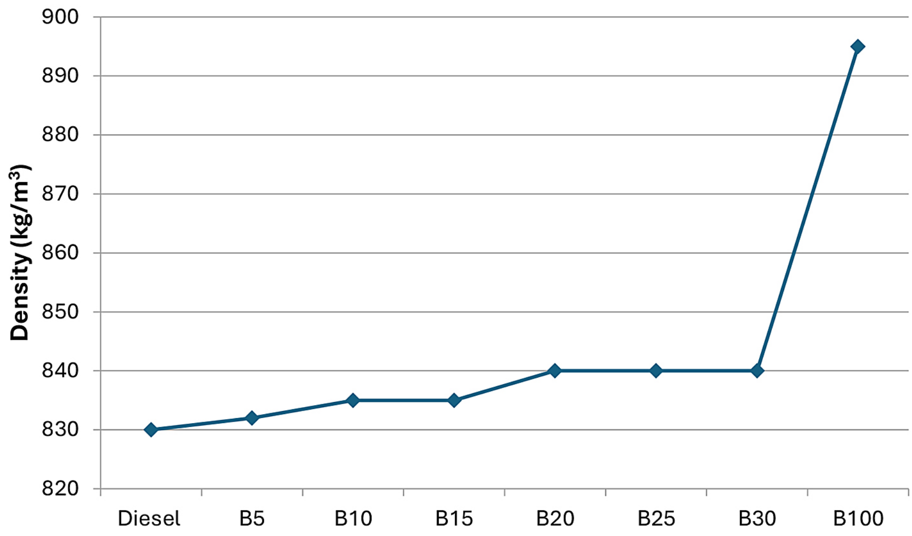

Figure 6. Comparison of density for various fuel blends

that strikes a balance between efficiency and environmental advantages (Alp *et al.*, 2017; Surakasi *et al.*, 2023).

EMISSION STUDIES

In the last ten years, biofuels such as blended gasoline and biodiesel, have started to find a role in the energy economy, because lowering CO_2 emissions is necessary for a sustainable transportation future (Ashikhmin *et al.*, 2024; Nanaki, 2009). In comparison to diesel fuel, the use of biodiesel results in higher brake specific fuel consumption and reduced smoke opacity (up to 60%). It was discovered that the B5 and B100 fuels had CO emissions that were 9% and 32% lower, respectively, than the diesel fuel (Buyukkaya, 2010). Under varying engine operating conditions of loads and speeds, the impact of biodiesel blends on gaseous emissions and particulate matter was examined. For all gasoline tests, the best decrease was obtained during medium engine load and speed settings, as opposed to low and high loads and speeds. The overall PM concentration was lowered by the increased rate of soot particle oxidation during the combustion cycle caused by burning B100, B50, and B20 (Arvesen *et al.*, 2021).

When compared to other biofuels, Hydrotreated Vegetable Oil (HVO) is shown to have higher CN and better stability. Its capacity to lower emissions without sacrificing efficiency is what makes it a "renewable diesel", and HVO is more cost-effective fuel. In terms of fuel usage, HVOB5 and HVOB10 are determined to be comparable to diesel fuel. All of the fuel combinations have been found to have reduced emissions by around 4–5% in CO_2, 10–15% in NO_x, and 25–45% in smoke (Rayapureddy *et al.*, 2022). Fuel consumption increased by 4% when palm oil fuel was used at a 20% mixing ratio (Damian *et al.*, 2025). Additionally, a 3% increase in volumetric efficiency was observed and compared to diesel fuel, it shows the highest value (Saleh *et al.*, 2024). In contrast to pure diesel, numerical studies show that all biodiesel mixes increase specific fuel consumption and mechanical efficiency under full load conditions while decreasing BTE, exhaust gas temperature, and indicated thermal efficiency (Kumar *et al.*, 2024).

CONCLUSIONS

This study has demonstrated that turning used cooking oil into biodiesel provides a workable and efficient way to recycle a material that is frequently thrown away. It also emphasizes the advantages for the environment of using biodiesel to cut down on pollution and greenhouse gas emissions. From an economic perspective, the study highlights the possible cost reductions and employment prospects linked to the utilization of leftover cooking oil for the manufacture of biodiesel. Going forward, more research and development in this area can improve product quality, streamline manufacturing processes, and encourage the general use of biodiesel as a sustainable energy source. In general, the creation of biodiesel from WCO serves as a concrete illustration of how creative resource management techniques may support the development of a more sustainable and greener future. The biofuel analysis test conforms that biodiesel generated were successful in all terms through biofuel analysis test. Gross calorific value, viscosity, water content, sulphur content, ash, flash and fire point were identified. biodiesel characterisation study, multiple blends B5, B10, B15, B20, B25, B30, and B100 were tested. It was evident from the data that the B20 mix performed the best. This implies that using B20 to increase engine efficiency and lower emissions is a viable and sustainable option and at the same time the emission are expected to be lower than the conventional fuel by 4–5%. The biofuel generated from WCO were able to utilize as a substitute combustible.

Acknowledgments

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REFERENCES

1. Alp, D., Larsson, J., Fransson, C., Bond, H.E., Schaefer, G.H., Gilliland, R.L., *et al.* (2017), The performance and emissions of diesel engines with biodiesel of sunan pecan seed and diesel oil blends, *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 277(1), 012045, doi: 10.1088/1757-899X/277/1/012045.
2. Aransiola, E., Betiku, E., Dio, I. and Ojumu, T. (2012), Production of biodiesel from crude neem oil feedstock and its emissions from internal combustion engines, *African Journal of Biotechnology*, Academic Journals, 11(22), doi: 10.5897/AJB11.2301.
3. Arvesen, A., Humpenöder, F., Navarrete Gutierrez, T., Fayad, M.A., Chaichan, M.T. and Dhahad, H.A. (2021), The effect of first generation biofuel on emission characteristics under variable conditions of engine speeds and loads in diesel engine, *Journal of Physics: Conference Series*, IOP Publishing, 1973(1), 012041, doi: 10.1088/1742-6596/1973/1/012041.
4. Ashikhmin, A., Verkhodanov, D., Piskunov, M. and Strizhak, P. (2024), Operational and Environmental Tests of Nanomembrane-Produced Rapeseed Biodiesel at a Small Biomass-Fuelled Power Plant, *Waste and Biomass Valorization*, Springer Science and Business Media B.V., 16(2), 881–900, doi: 10.1007/S12649-024-02706-X/TABLES/3.
5. Avinash, A. and Murugesan, A. (2017), Economic analysis of biodiesel production from waste cooking oil, *Energy Sources, Part B: Economics, Planning, and Policy*, Taylor & Francis, 12(10), 890–894, doi: 10.1080/15567249.2017.1319438.
6. Azad, A.K., Rasul, M.G., Giannangelo, B. and Islam, R. (2015), Comparative study of diesel engine performance and emission with soybean and waste oil biodiesel fuels, *International Journal of Automotive and Mechanical Engineering*, Universiti Malaysia Pahang, 12(1), 2866–2881, doi: 10.15282/IJAME.12.2015.6.0241.
7. Barua, P.K. (2011), Biodiesel from seeds of jatropha found in Assam, India, *International Journal of Energy, Information and Communications*, 2(1).
8. Benny, A., Achar, R., Harsha, T.S. and Vadiraj, K.T. (2024), Biodiesel production from various nonedible plant seeds via transesterification process as an alternate feedstock, *Handbook of Emerging Materials for Sustainable Energy*, Elsevier, 451–466, doi: 10.1016/B978-0-323-96125-7.00010-1.
9. Buyukkaya, E. (2010), Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics, *Fuel*, Elsevier, 89(10), 3099–3105, doi: 10.1016/J.FUEL.2010.05.034.
10. Cadenas, A. and Cabezudo, S. (1998), Biofuels as sustainable technologies: perspectives for less developed countries, *Technological Forecasting and Social Change*, North-Holland, 58(1–2), 83–103, doi: 10.1016/S0040-1625(97)00083-8.
11. Chhetri, A.B., Watts, K.C. and Islam, M.R. (2008), Waste Cooking Oil as an Alternate Feedstock for Biodiesel Production, *Energies 2008, 1,* 3–18, Molecular Diversity Preservation International, 1(1), 3–18, doi: 10.3390/EN1010003.
12. Damian, C.S., Devarajan, Y., Jayabal, R. and Raja, T. (2025), Enhancing marine diesel engine compatibility with sustainable fuels: Key factors and adjustments, *Marine Pollution Bulletin*, Pergamon, 215, 117836, doi: 10.1016/J.MARPOLBUL.2025.117836.
13. Das, A., Kumbhakar, B., Pachfule, P., Baskar, G., Li, H., Kodgire, P. and Rokhum, S.L. (2024), Valorization of Bambusa striata shavings into functional superparamagnetic material and its application in biodiesel production: Response surface optimization, kinetics, thermodynamics and economic assessment, *Process Safety and Environmental Protection*, Elsevier, 189, 894–910, doi: 10.1016/J.PSEP.2024.06.116.
14. Demirbaş, A. (2003), Biodiesel fuels from vegetable oils via catalytic and non-catalytic supercritical alcohol transesterifications and other methods: a survey, *Energy Conversion and Management*,

Pergamon, 44(13), 2093–2109, doi: 10.1016/S0196-8904(02)00234-0.

15. Demirbas, A. (2009), Characterization of Biodiesel Fuels, *Energy Sources, Part A*, Taylor & Francis Group, 31(11), 889–896, doi: 10.1080/15567030801904202.
16. Dhawane, S.H., Karmakar, B., Ghosh, S. and Halder, G. (2018), Parametric optimisation of biodiesel synthesis from waste cooking oil via Taguchi approach, *Journal of Environmental Chemical Engineering*, Elsevier, 6 (4), 3971–3980, doi: 10.1016/J.JECE.2018.05.053.
17. Escobar, J.C., Lora, E.S., Venturini, O.J., Yáñez, E.E., Castillo, E.F. and Almazan, O. (2009), Biofuels: Environment, technology and food security, *Renewable and Sustainable Energy Reviews*, Pergamon, 13(6–7), 1275–1287, doi: 10.1016/J.RSER.2008.08.014.
18. Gebremariam, S.N. and Marchetti, J.M. (2018), Economics of biodiesel production: Review, *Energy Conversion and Management*, Pergamon, 168, 74–84, doi: 10.1016/J.ENCONMAN.2018.05.002.
19. Graboski, M.S. and McCormick, R.L. (1998), Combustion of fat and vegetable oil derived fuels in diesel engines", *Progress in Energy and Combustion Science*, Pergamon, 24(2), 125–164, doi: 10.1016/S0360-1285(97)00034-8.
20. Hasan, M., Abedin, M.Z., Amin, M. Bin, Nekmahmud, M. and Oláh, J. (2023), Sustainable biofuel economy: A mapping through bibliometric research, *Journal of Environmental Management*, Academic Press, 336, 117644, doi: 10.1016/J.JENVMAN.2023.117644.
21. Hinduja, K., Achar, R. and Vadiraj, K.T. (2024), Microalgae as a source of sustainable energy resource for biofuels: a review, *Handbook of Emerging Materials for Sustainable Energy*, Elsevier, 467–492, doi: 10.1016/B978-0-323-96125-7.00002-2.
22. Hirkude, J.B., Randhir, J. and Belokar, V.W. (2018), Techno-economic Conversion of Waste Fried Oil into Biodiesel through Transesterification, *IOP Conference Series: Materials Science and Engineering*, 377, Institute of Physics Publishing, doi: 10.1088/1757-899X/377/1/012160.
23. Kawentar, W.A. and Budiman, A. (2013), Synthesis of biodiesel from second-used cooking oil, *Energy Procedia*, Elsevier, Vol. 32, pp. 190–199, doi: 10.1016/J.EGYPRO.2013.05.025.
24. Kumar, D., Kachhap, S. and Thokchom, S.S. (2024), Numerically comparative assessment of different biodiesel & its blends on performance, combustion and emission characteristics, *Industrial Crops and Products*, 209, doi: 10.1016/j.indcrop.2023.117900.
25. Lee, A.F., Bennett, J.A., Manayil, J.C. and Wilson, K. (2014), Heterogeneous catalysis for sustainable biodiesel production via esterification and transesterification, *Chem. Soc. Rev*, 43, 7887, doi: 10.1039/c4cs00189c.
26. Lhawang, T., Sirigeri, S., Menon, S. and Vadiraj, K.T. (2021), Azadirchta excelsa seed oil, a potential non-conventional biodiesel feedstock, *Environmental Challenges*, Elsevier, 3, 100057, doi: 10.1016/J.ENVC.2021.100057.
27. Lin, C.Y. and Wu, X.E. (2022), Determination of cetane number from fatty acid compositions and structures of biodiesel, *Processes* 10, 1502, Multidisciplinary Digital Publishing Institute, 10(8), 1502, doi: 10.3390/PR10081502.
28. Long, E. and Carlsten, C. (2022), Controlled human exposure to diesel exhaust: results illuminate health effects of traffic-related air pollution and inform future directions, *Particle and Fibre Toxicology*, BioMed Central Ltd, 19(1), 1–35, doi: 10.1186/S12989-022-00450-5/FIGURES/1.
29. Malik, K., Capareda, S.C., Raj Kamboj, B., Malik, S., Singh, K., Arya, S. and Kumar Bishnoi, D. (2024), Biofuels Production: A Review on Sustainable Alternatives to Traditional Fuels and Energy Sources, *Fuels 5,* 157–175, Multidisciplinary Digital Publishing Institute, doi: 10.3390/FUELS5020010.
30. Nanaki, E.A. (2009), Environmental comparison of the use of biodiesel and gasoline for transportation - A case study for Athens, *Indoor and Built Environment*, SAGE PublicationsSage UK: London, England, 18(5), 416–423, doi: 10.1177/1420326X09346131;WEBSITE:WEBSITE:SAGE;WGROUP:STRING:PUBLICATION.
31. Patel, R., Rajaraman, T.S., Rana, P.H., Ambegaonkar, N.J. and Patel, S. (2025), A review on techno-economic analysis of lignocellulosic biorefinery producing biofuels and high-value products, *Results in Chemistry*, Elsevier, 13, 102052, doi: 10.1016/J.RECHEM.2025.102052.
32. Pugh, S., McKenna, R., Moolick, R. and Nielsen, D.R. (2011), Advances and opportunities at the interface between microbial bioenergy and nanotechnology, *The Canadian Journal of Chemical Engineering*, John Wiley & Sons, Ltd, 89(1), 2–12, doi: 10.1002/CJCE.20434.
33. Puri, M., Abraham, R.E. and Barrow, C.J. (2012), Biofuel production: Prospects, challenges and feedstock in Australia, *Renewable and Sustainable Energy Reviews*, Pergamon, 16(8), 6022–6031, doi: 10.1016/J.RSER.2012.06.025.
34. Rayapureddy, S.M., Matijošius, J., Rimkus, A., Caban, J. and Słowik, T. (2022), Comparative study of combustion, performance and emission characteristics of hydrotreated vegetable oil–biobutanol fuel blends and diesel fuel on a CI engine, *Sustainability 14,* 7324, Multidisciplinary Digital Publishing Institute, doi: 10.3390/SU14127324.
35. Rocha-Meneses, L., Hari, A., Inayat, A., Yousef,

L.A., Alarab, S., Abdallah, M., Shanableh, A., *et al.* (2023), Recent advances on biodiesel production from waste cooking oil (WCO): A review of reactors, catalysts, and optimization techniques impacting the production, *Fuel*, Elsevier, 348, 128514, doi: 10.1016/J.FUEL.2023.128514.

36. Sakthimurugan, V., Lakshmikanth, G., Balaji, N., Roopashree, R., Kumar, D. and Devarajan, Y. (2025), Green hydrogen revolution: Advancing electrolysis, market integration, and sustainable energy transitions towards a net-zero future, *Results in Engineering*, Elsevier, 26, 104849, doi: 10.1016/J.RINENG.2025.104849.
37. Saleh, F.A., Allawi, M.K., Imran, M.S. and Samarmad, A.O. (2024), A Simulation of the Impact of Biodiesel Blends on Performance Parameters in Compression Ignition Engine, *Journal of Ecological Engineering*, Polish Society of Ecological Engineering (PTIE), 25(7), 1–7, doi: 10.12911/22998993/185889.
38. Sirigeri, S., Vadiraj, K.T. and Belagali, S.L. (2022), Tabebuia rosea: a prospective non-edible biodiesel feedstock, *Biofuels*, Taylor & Francis, 13(1), 17–19, doi: 10.1080/17597269.2019.1627017.
39. Sivaramakrishnan, K. and Ravikumar, P. (2011), Determination of higher heating value of biodiesels, *International Journal of Engineering Science and Technology*, 3(11), 7981–7987.
40. Surakasi, R., Srinivasa Rao, Y., Kalam, S.A. and Begum, N. (2023), Emissions and Performance of Diesel Engines Correlated with Biodiesel Properties, *Journal of Engineering*, John Wiley & Sons, Ltd, 2023(1), 5274325, doi: 10.1155/2023/5274325.
41. Tarigan, J.B., Ginting, B., Perangin-angin, S., Sari, R.N., Sianipar, P.F. and Sitepu, E.K. (2023), Homogenizer-intensified amidation of free fatty acids in waste cooking oil for biodiesel production, *South African Journal of Chemical Engineering*, Elsevier, 46, 271–276, doi: 10.1016/J.SAJCE.2023.08.011.
42. Ülgen, A.İ., Çelebi, Y. and Aydın, H. (2025), High proportion of biofuel replacement for conventional diesel using safflower biodiesel and diethyl ether blends in a CNG-powered RCCI operation of a diesel engine, *Renewable Energy*, Pergamon, 246, 122919, doi: 10.1016/J.RENENE.2025.122919.