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Correlation between Physical Properties and Specific Fuel Consumption in Jatropha -Used Cooking Oil Biodiesel Mixtures

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Biodiesel; physical properties; spray angle; specific fuel consumption.

Abstract
This study was motivated by the need to understand the influence of using waste jatropha biodiesel on the physical properties of fuel and the performance of diesel engines. The primary aim was to determine the relationship between the fuel's physical properties, spray angle, and specific fuel consumption (SFC) at various load levels. The methodology employed included measurements of density, viscosity, flash point, calorific value, spray angle, and SFC for different blends of waste jatropha biodiesel and diesel (B5, B10, B15, B20). The research results demonstrate an increase in density, kinematic viscosity, and flash point, along with a decrease in calorific value, as the biodiesel content increases. The density of the biodiesel mixture ranges from 823 kg/m³ at B5 to 836.50 kg/m³ at B20. The kinematic viscosity increases from 3.9 cSt at B5 to 5.2 cSt at B20, and the flash point rises from 112.9°C at B5 to 128.7°C for B20. Meanwhile, the calorific value decreases from 10308.2670 cal/g at B5 to 10133.8280 cal/g for B20. A strong correlation exists between density and kinematic viscosity with the spray angle, exhibiting R^2 values of 0.9141 and 0.8287, respectively. The correlation between the fuel's physical properties and the specific fuel consumption (SFC) is also substantial, marked by high R^2 values above 0.93. These findings provide a solid foundation for the development of more optimal biodiesel formulations.

INTRODUCTION

Industrial growth and energy needs have increased significantly in this era of modern industrialization. However, the availability of the primary energy source, fossil fuels, is increasingly limited, thus encouraging the search for renewable energy alternatives (Maftuchah et al., 2020). The use of fossil fuels is also known to contribute significantly to environmental pollution, especially greenhouse gas emissions, which trigger global climate change (Afandi & Wibawa, 2022).

In response to this problem, vegetable oils were identified as a potential source for biodiesel production. Biodiesel is a form of renewable energy that can reduce dependence on fossil fuels and mitigate adverse environmental impacts (Deshmukh et al., 2021; Maftuchah et al., 2020). Biodiesel has several advantages, such as biodegradable properties and lower emissions (Xu et al., 2022). However, there are also several disadvantages, such as relatively high production costs and issues related to land use (Brahma et al., 2022).

There is a tendency in the industry to use edible raw materials as a source of biodiesel, such as palm oil and soybean oil (Ramos et al., 2019). This phenomenon causes controversy because it can affect food availability and prices (Brahma et al., 2022), as well as have an impact on food security in various regions (Ewunie et al., 2021). Therefore, it is important to explore alternative sources of non-edible vegetable oils, such as jatropha oil and used cooking oil, as raw materials for biodiesel to overcome this problem.

Jatropha oil is a source of non-edible vegetable oil that has attracted attention as a raw material for biodiesel (Riayatsyah et al., 2022). One of the main advantages of jatropha oil is its ability to grow on less fertile land, so it does not compete with food agricultural land (Snehi et al., 2022). In addition, this plant is resistant to pests and diseases, so it can reduce the use of pesticides and minimize environmental impacts. However, jatropha oil has several disadvantages, including its relatively high viscosity. High viscosity can cause problems in fuel use, such as filter blockage and residue deposition in the engine (Che Hamzah et al., 2020).

Meanwhile, waste cooking oil is a byproduct of frying oil and has potential as a source of biodiesel (Park et al., 2019). Using used cooking oil as a raw material for biodiesel can help reduce resource waste and environmental pollution. Due to its nature as waste product, used cooking oil becomes an economical and sustainable fuel source (Suzihaque et al., 2022). However, used cooking oil also has its drawbacks. High free fatty acid (FFA) content and contaminants can pose challenges in the biodiesel production process and affect the quality of the final fuel.

Although much research has been conducted on using jatropha oil and cooking oil as a source of biodiesel (Abed, 2018), most of these studies focus on using these two oils separately. Research combining these two types of oil as biodiesel raw material is still rare. This condition opens up opportunities to further explore the combination of jatropha oil and used cooking oil in biodiesel production, hoping to create a fuel that has the advantages of both types of oil and reduces the disadvantages of each (Mariono et al., 2023).

The physical properties of a fuel play an essential role in determining the quality and performance of that fuel when used in an engine. Parameters such as viscosity, density, heating value, and flash point are the leading indicators often used to measure fuel quality (Wahyudi & Krisdiyanto, 2022). Viscosity affects fuel flow, density relates to the energy that can be produced per unit volume, calorific value indicates the energy that can be produced per unit mass, and flash point relates to the safety of fuel use. In addition, fuel injection characteristics, such as spray angle and specific fuel consumption (SFC), are also significant, as they affect combustion efficiency and pollutant emissions.

Considering the importance of these physical properties, this research aims to determine the relationship between the biodiesel physical properties of jatropha-used cooking oil mixture fuel with spray angle and SFC in diesel engines. This correlation is essential for optimizing fuel formulation and improving engine performance while reducing environmental impact. The results of this research can significantly contribute to the development of more efficient and environmentally friendly biodiesel.

RESEARCH METHODS

Materials

The oil raw materials used as the basis for biodiesel are jatropha oil and used cooking oil. Jatropha oil was obtained from the TEKUN JAYA shop in Yogyakarta, Indonesia while cooking oil was obtained from the local market. The characteristics of each oil are presented in Table 1 below.

Table 1. Physical properties of jatropha oil and used cooking oil

Raw materials	Density (kg/m^3)	Viscosity (cSt)	Flash point (ºC)	Caloric value (kal/g)
Jatropha oil	904.97	48.1	223.3	8867.025
Used cooking oil	842.19	7.4	186.3	9527.643

Biodiesel Production

The biodiesel production process includes two main reactions, namely, esterification and transesterification. In the esterification stage, jatropha oil was reacted with methanol (22.5% of the oil volume), which had been mixed with 0.5% of the oil volume of Sulfuric Acid (H_2SO_4) at a temperature of 60°C for 60 minutes. Then, the oil deposition process takes 12 hours to be separated from the glycerol. After that, the oil was washed with water at 65°C then dried at 105°C to remove the water content. In the transesterification stage, the oil, which had undergone the esterification process, was reacted again with methanol (15% of the oil volume) which had been mixed with the base catalyst Potassium Hydroxide (KOH) at 1% of the oil volume at a temperature of 60°C for 60 minutes. Next, the settling, washing, and drying process were carried out to produce pure biodiesel or methyl ester. The exact process is applied to used cooking oil. Then, jatropha biodiesel was mixed with used cooking biodiesel in a 1:1 ratio, and this mixture is mixed with diesel oil with variations B5, B10, B15, and B20. Stirring was carried out at 70°C for 60 minutes.

Evaluation of Fuel Physical Characteristics and Diesel Engine

Each sample was tested to determine its physical characteristics, such as density, viscosity, heating value, and flash point. Density testing was done by weighing 50 ml of sample at a temperature of 40°C using a Fujitsu FS-AR210 digital scale. Sample viscosity measurements at a temperature of 40°C were carried out using an NDj 8 S Viscometer. The calorific value test was carried out according to the ASTM D 240 - 02 method, using a Bomb Calorimeter Parr 6050. The flash point was measured using the Cleveland Open Cup method.

Injection testing was also conducted to determine the fuel spray angle. The fuel spray angle was obtained by capturing video during the fuel spraying process. The produced video was converted into image format using Adobe Premiere Pro CC 2017 software. Subsequently, the measurement of the injection angle on the obtained images was conducted using Autodesk Inventor Pro 2017 software. The schematic of injection test equipment is presented in Figure 1.

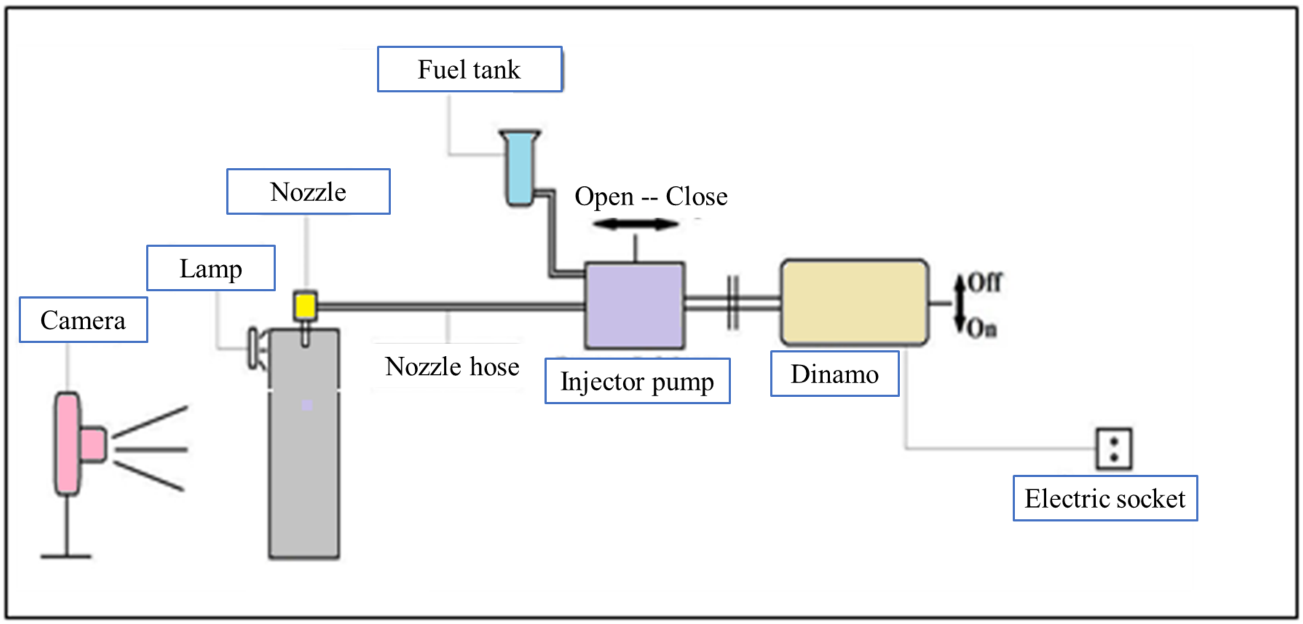

Figure 1. Schematic of injection test equipment

Diesel engine performance evaluation was carried out using a Jiangdong diesel engine with a load of 1 to 5 lamps, each with a power of 500 watts. This test obtains data regarding electrical power and fuel consumption rate, which were then used to calculate specific fuel consumption. Specific Fuel Consumption (SFC) can be calculated using the following formula:

$$SFC = \frac{\dot{m}_f}{P} \quad \text{(Equation 1)}$$

Where SFC is Specific Fuel Consumption (kg/kW.h) , $\dot{m}_f$ is the fuel flow rate (kg/hour) and P is power output (kW). The fuel flow rate is calculated using the following equation:

$$\dot{m}_f = \left(\frac{V_f \, x \, \rho_f}{t_f}\right) x \; 3600 \quad \text{(Equation 2)}$$

Where ρ_f is the density (g/ml), V_f is the volume of fuel tested (ml) and t_f is the time taken to consume the volume of fuel tested (seconds). The diesel engine specifications are provided in Table 2. The schematic of engine performance test equipment is presented in Figure 2.

Table 2. Diesel engine specification

Component	**Specification**
Brand	Jiangdong
Type	R180N Hopper (Horizontal 4 Stroke)
Maximum Power	8 HP / 2600 rpm
Average Power	7.5 HP / 2600 rpm
Bore x Stroke	80 mm x 80 mm
Cylinder Capacity	402 cc
Number of Cylinders	Single Cylinder
Starting System	Crank / Hand Start
Cooling System	Hopper
Combustion System	Indirect
Governor System	Mechanical
Compression Ratio	21 : 1

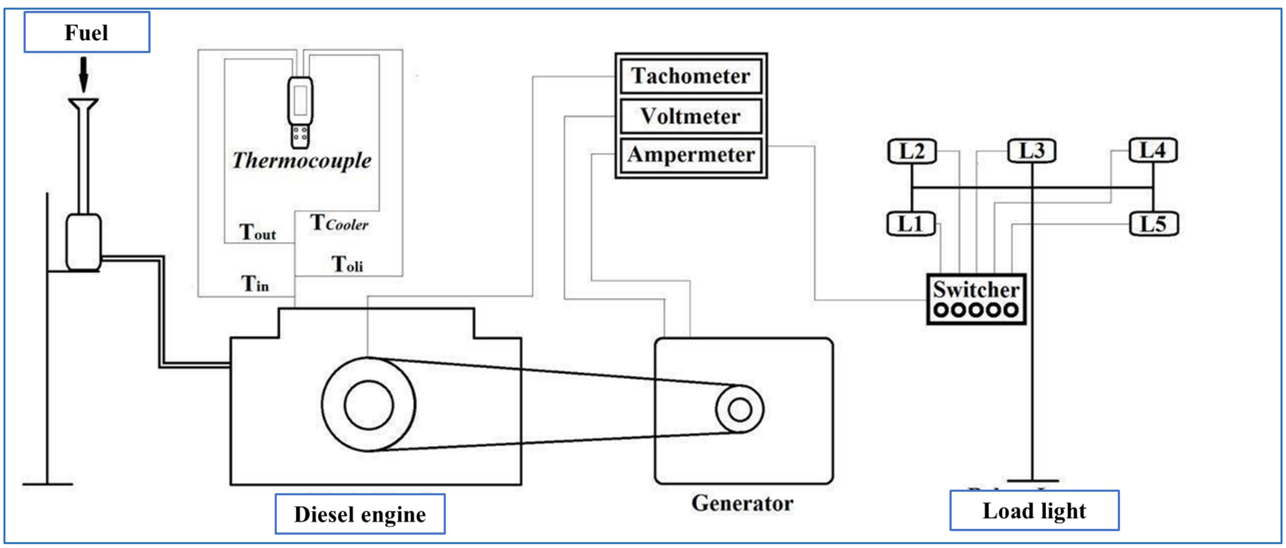

Figure 2. Diesel engine performance test equipment schematic

RESULTS AND DISCUSSION

Physical properties of jatropha -used cooking oil biodiesel

The physical properties of a mixture of jatropha-used cooking oil biodiesel with diesel oil levels B5, B10, B15, and B20 are presented in Figure 3. Physical properties include density, viscosity, flash point, and heating value. Fuel density is the fuel mass per unit volume, usually measured in kilograms per cubic meter (kg/m^3). Density is an essential physical property of fuel that affects engine performance and exhaust emissions (Zhang et al., 2022). Based on the data obtained, it can be observed that the density of 1:1 jatropha-used cooking oil biodiesel, which has been combined with diesel, increases along with the increase in biodiesel concentration in the mixture. The density for B5 is 823 kg/m^3, increases to 829 kg/m^3 for B10, 832 kg/m^3 for B15, and reaches 836.50 kg/m^3 for B20. This increase indicates that along with a higher concentration of biodiesel in the mixture, the mass per unit fuel volume also increases (Bukkarapu et al., 2017).

This increase in density has several important implications for engine performance and emissions. A higher density means more fuel mass can enter the combustion chamber for each combustion cycle (Acharya et al., 2017), potentially increasing the engine's power output. However, too high a density can also cause problems such as increased load on the injectors and fuel pump and incomplete combustion, which can ultimately affect emissions and engine efficiency.

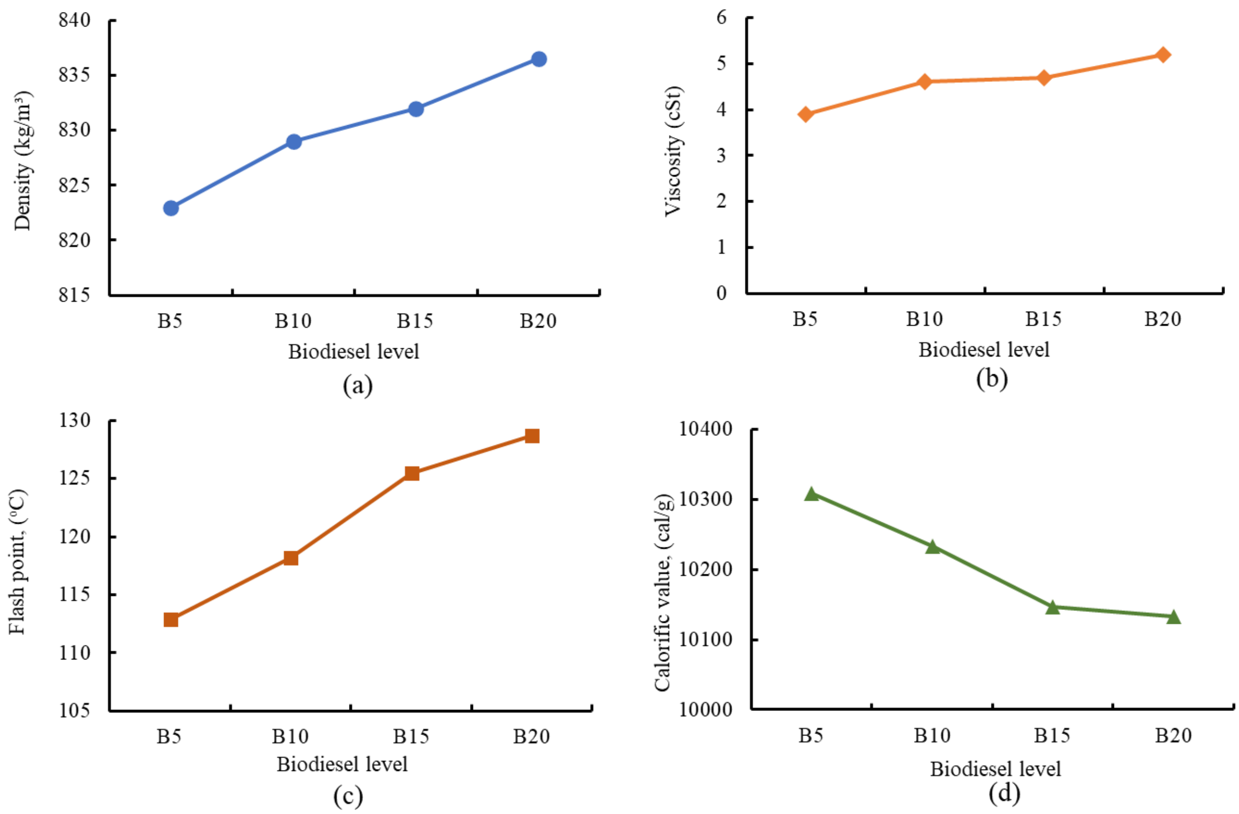

Figure 3. Physical properties of a mixture of jatropha-used cooking biodiesel with diesel oil levels B5, B10, B15, and B20, (a) density, (b) kinematic viscosity, (c) flash point, and (d) heating value

Viscosity is a measure of a fluid's resistance to deformation. For fuels, viscosity is an important parameter because it influences the fuel injection and atomization process in the engine (Saputro et al., 2020), affecting combustion efficiency and emissions. Viscosity that is too high can cause problems in spraying and mixing fuel with air (Acharya et al., 2017), while too low viscosity can cause leaks and pressure instability. Figure 3 (b) shows that the viscosity of jatropha-used cooking oil biodiesel with diesel increases gradually as the concentration of biodiesel in the mixture increases. The viscosity for B5 is 3.9 cSt, then increases to 4.6 cSt for B10, 4.7 cSt for B15, and finally reaches 5.2 cSt for B20. These results show that the higher the concentration of biodiesel in the mixture, the higher the fluid's resistance to flow (Wahyudi et al., 2020).

This increase in viscosity indicates that when the concentration of jatropha-used cooking biodiesel in the mixture increases, the resistance to flow also increases. This resistance can affect the fuel injection process, where higher viscosity can affect the formation of fuel droplets and mixing with air, ultimately affecting the combustion quality in the engine combustion chamber (Wahyudi et al., 2020).

The flash point is the lowest temperature at which fuel vapor can form to form a combustible air mixture when an ignition source is present. Flashpoint is an essential indicator of the ability of a fuel to vaporize and form a flammable air-fuel mixture (Carareto et al., 2012). Fuels with a low flash point are more volatile and pose a higher risk, while fuels with a high flash point tend to be more stable and safer from the fire risk.

Based on the data shown in Figure 3 (c), the flash point of the mixture of jatropha-used cooking oil biodiesel and diesel fuel increases as the concentration of biodiesel in the mixture increases. The flash point for B5 is

112.9°C, increasing to 118.2°C for B10, 125.5°C for B15, and reaching 128.7°C for B20. This increase in flash points proves that biodiesel blends with higher biodiesel concentrations have better fire control and storage safety characteristics.

The calorific value of fuel measures the energy that fuel can produce per unit mass or volume when burned. This value is significant because it determines how efficiently the fuel can produce energy when used in an engine. Fuel with a high heating value can produce more energy per unit of mass or volume, making it more efficient, while fuel with a low heating value requires greater consumption to produce the same energy. (Acharya et al., 2017).

Based on the data presented (Figure 3.d), the calorific value of the mixture of jatropha-used cooking biodiesel and diesel fuel decreases as the concentration of biodiesel in the mixture increases. The calorific value for B5 is 10308.2670 cal/g, decreasing slightly to 10233.7445 cal/g for B10, 10147.4480 cal/g for B15, and 10133.8280 cal/g for B20. This decrease indicates that the higher the concentration of biodiesel in the mixture, the lower the energy that can be produced per gram of fuel (Wahyudi et al., 2020). This decrease in heating value can affect diesel engine performance. An engine operating on a lower calorific value fuel may require more fuel to produce the same power as a higher calorific value fuel.

Based on the results of these physical properties, this jatropha-used cooking oil biodiesel blend shows great potential for use as fuel in combination with diesel oil. The benefits of using biodiesel, apart from anticipating the depletion of fossil fuel reserves, include its impact on reducing environmental pollution(Suzihaque et al., 2022). On the other hand, the utilization of jatropha, which is a non-edible material, and used cooking oil, which is a waste product, reduces the cost of raw materials, thus it is expected to be more economical.

Influence of physical properties on injection angle

Fuel spray angle refers to the angle at which fuel is sprayed into the combustion chamber through the injector nozzle on a diesel engine. The optimal spray angle is critical because it affects mixing fuel with air, combustion, fuel efficiency, and pollutant emissions (Hakim et al., 2022). A wider spray provides a larger surface area for mixing and burning, increasing combustion efficiency and reducing emissions (Zhao et al., 2019).

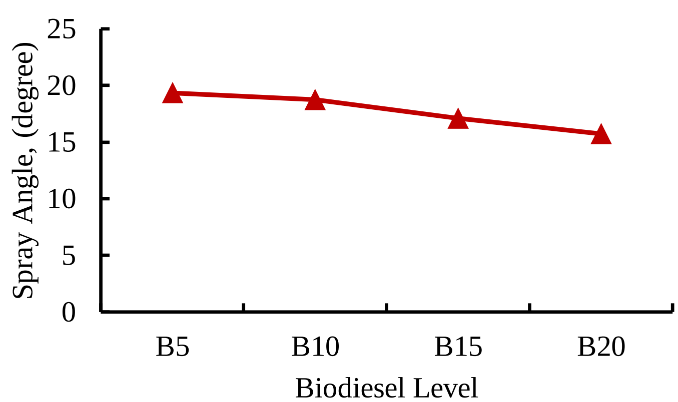

Figure 4. Spray angle of the injection of jatropha-used cooking biodiesel mixture with diesel oil levels B5, B10, B15, and B20

The injection angle test results in Figure 4 show a decrease in the spray angle with increasing biodiesel concentration in the mixture. For the B5 mixture, the spray angle is 19.34°, which then decreases to 18.74° for B10, 17.09° for B15, and 15.73° for B20. This decrease shows that the higher the biodiesel concentration, the narrower the spray angle.

Based on the regression analysis (Figure 5), there is a correlation between the physical properties of the fuel, such as density and viscosity, and the spray angle. A high R^2 value for each correlation indicates that these variables have a strong linear relationship. The correlation between density and spray angle shows an R^2 value of 0.9141. This phenomenon indicates that the fuel density significantly impacts the spray angle. The higher the density, the smaller the spray angle tends to be.

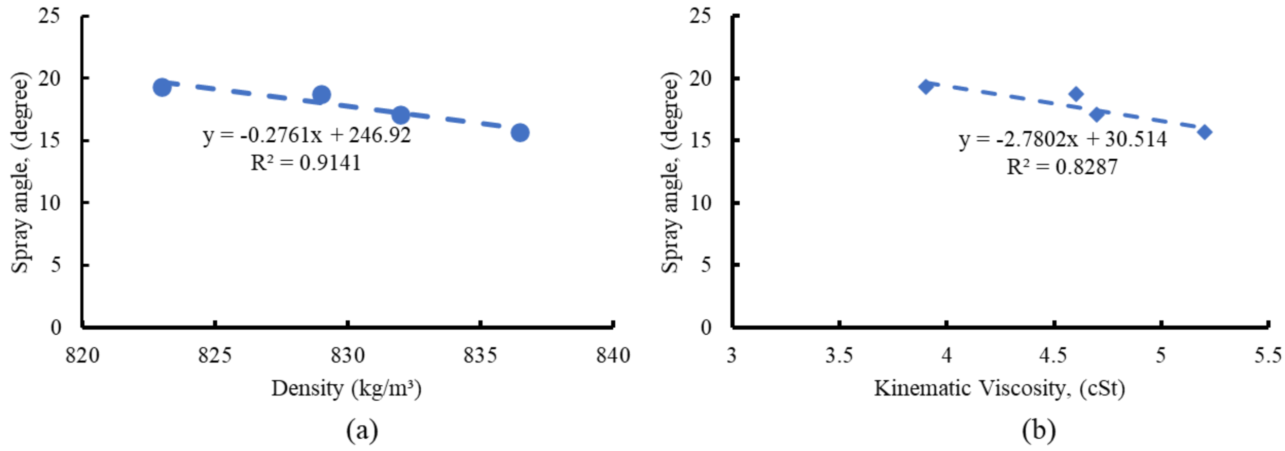

Figure 5. Relationship of density and viscosity to injection angle, (a) density, (b) kinematic viscosity

Furthermore, viscosity against the spray angle has an R^2 of 0.8287. High viscosity results in slower fuel flow, reducing the spray angle and the potential for optimal distribution in the combustion chamber (Rafdi et al., 2022).

Specific fuel consumption

Specific fuel consumption (SFC) measures engine fuel efficiency expressed in fuel weight per unit of power (usually kilograms per kilowatt hour, kg/kW.hour) produced. This value is significant because it shows how efficiently the engine converts fuel into mechanical energy. A low SFC indicates high efficiency and is a key performance indicator for an engine.

Table 3. Specific fuel consumption of a mixture of jatropha-used cooking oil biodiesel with diesel oil levels B5, B10, B15, and B20

Load (Watt)	**Specific Fuel Consumption (kg/kW.hour)**			
	B5	**B10**	**B15**	**B20**
500	0.23	0.23	0.23	0.27
1000	0.20	0.21	0.21	0.23
1500	0.25	0.25	0.26	0.27
2000	0.35	0.36	0.37	0.37
2500	0.48	0.49	0.50	0.51

The SFC data presented in Table 3 shows an increase in SFC with increasing load for all variations of biodiesel. At a load of 500 Watts, the SFC is relatively uniform for B5, B10, and B15, but B20 shows a higher value. As the load increases, the SFC for all biodiesel variations continues to increase, with the SFC B20 value always being the highest at every load level. This trend shows that although the machine can operate higher loads, its efficiency decreases, as indicated by an increase in SFC.

SFC data and its relationship to load can be related to the fuel's physical properties and spray angle. As explained previously, physical properties such as density and viscosity are correlated with the spray angle. The optimal spray angle can influence the mixing and combustion processes, affecting engine efficiency and SFC.

Correlation of physical properties with SFC

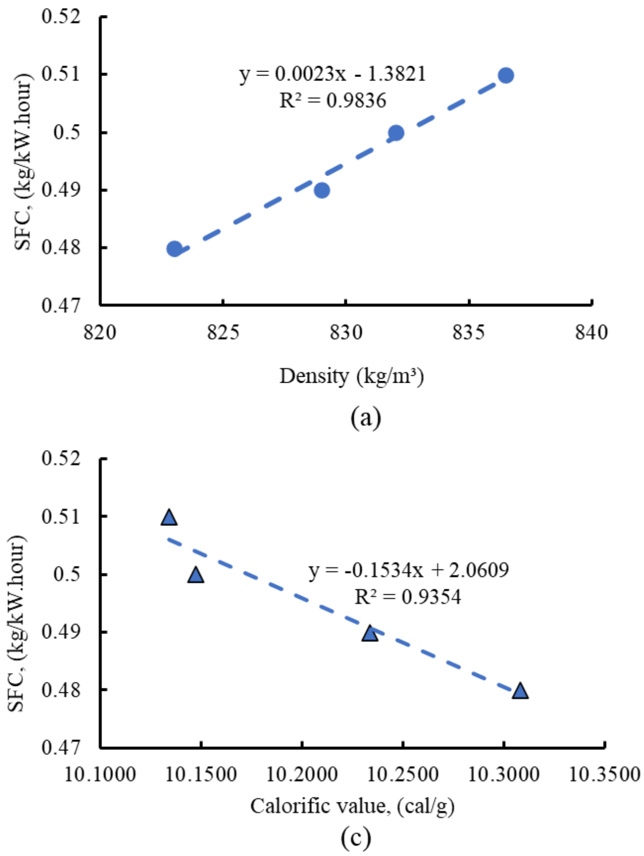

Figure 6. Relationship of physical properties to SFC, (a) density, (b) kinematic viscosity, (c) heating value, and (d) flash point

Based on the trendline equation obtained (Figure 6. a), there is a relationship between fuel density and specific fuel consumption (SFC). The higher the fuel density, the SFC will also tend to increase. This phenomenon can be interpreted to mean that fuel with a higher density tends to have lower energy conversion efficiency in the engine, so it requires more fuel to produce the same power.

The trendline equation obtained (Figure 6. b) shows a positive relationship between fuel viscosity and Specific Fuel Consumption (SFC). When fuel viscosity increases, SFC tends to increase. This increase can mean that fuel with a higher viscosity requires more energy to produce the same power, so its efficiency is low. High viscosity can cause fuel flow restrictions and reduce combustion efficiency, so more fuel is needed to produce the same power. The higher the fuel viscosity, the narrower the spray angle because thicker fuel tends not to spread when sprayed (Rafdi et al., 2022).

The spray angle is an essential parameter that influences the atomization process and distribution of fuel in the combustion chamber, ultimately affecting combustion efficiency and fuel consumption. Therefore, high-viscosity fuels with smaller spray angles may require more energy to produce the same power, reflected in a higher SFC.

Figure 6(c) shows a positive correlation between heating value and SFC. Fuels with higher heating values can provide more energy per unit mass, potentially lowering SFC. The correlation between heating value and SFC is robust, indicating that fuel heating value significantly influences engine performance.

Based on the data presented in Figure 6 (d), there is a positive correlation between flash points and SFC. This condition indicates that fuels with a higher flash point also tend to have a higher SFC. Fuels with higher flash points are considered more difficult to evaporate and require more energy to burn, increasing specific fuel consumption.

CONCLUSION

Jatropha-used cooking biodiesel mixed with diesel at levels B5 to B20 has been proven to be able to be used as diesel engine fuel. The more biodiesel content causes an increase in density, viscosity, flash point, and a decrease in heating value and spray angle. There is a close relationship between physical properties and injection angle, as can be seen from the high R^2 values in each correlation. SFC analysis shows increased fuel consumption with operational load and biodiesel content. There is a strong correlation between physical properties and SFC. This correlation shows that the physical properties of the fuel have a significant influence on the efficiency of fuel use. Based on these findings, there is potential for developing a more optimal biodiesel formulation. Future research could concentrate on optimizing the jatropha-used cooking oil biodiesel blend to discover a more precise biodiesel mixture proportion that minimizes fuel consumption while still preserving engine performance.

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