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CORRELATION OF THE PHYSICAL PROPERTIES OF NYAMPLUNG OIL-BASED BIODIESEL: DENSITY, VISCOSITY, CALORIFIC VALUE, AND FLASH POINT

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Abstrak.
The increasing demand for renewable energy has intensified the development of biodiesel from various feedstocks, including non-food sources like nyamplung oil (Calophyllum inophyllum). However, the physical properties of biodiesel, such as density, viscosity, flash point, and calorific value, critically impact its performance, safety, and energy efficiency. This study aims to analyze the correlations among these key physical parameters in biodiesel blends of nyamplung oil and palm oil. Biodiesel was produced via esterification and transesterification, blended in varying ratios, and subjected to standardized testing. Regression analysis revealed a strong positive correlation between density and viscosity (R^2 = 0.8834) and viscosity and flash point (R^2 = 0.9343), while density and calorific value showed a strong negative correlation (R^2 = 0.9522). Flash point also negatively correlated with calorific value (R^2 = 0.8570). These results indicate that fatty acid composition, particularly chain length and unsaturation level, significantly affects biodiesel's physical and energetic characteristics. Understanding these interrelations is essential for optimizing biodiesel blends to balance combustion efficiency, fuel safety, and storage stability. This research contributes valuable insights for biodiesel formulation from local resources, promoting sustainable energy solutions. Future studies should explore the impact of these physical parameters on engine emissions and durability, as well as blending effects with other indigenous feedstocks to expand applicability.

Keywords: biodiesel; calophyllum inophyllum; palm; physical properties; correlation

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INTRODUCTION

Global energy demand that continues to increase as population growth and industrialization leads to massive exploitation of fossil fuels, the availability of which is depleting (Deshmukh et al., 2021; Haregu et al., 2023). To overcome this, biodiesel is one of the renewable energy alternatives that continues to be developed because it comes from plant-based raw materials and has environmentally friendly characteristics and can be biodegradable (Eloka-Eboka et al., 2017; Siltonga et al., 2013; Xu et al., 2022).

Biodiesel is a compound of monoalkyl esters of long-chain fatty acids obtained through the process of transesterification of triglycerides, both from vegetable oils and animal fats, with alcohols such as methanol or ethanol (Hoekman et al., 2012). The physical properties of biodiesel are greatly influenced by the chemical structure of the fatty acids that make up them, such as the length of the carbon chain, the degree of unsaturation, and the branching of the chain (Rodrigues Jr et al., 2006). Therefore, the variety of raw materials will produce different characteristics of biodiesel, so that the mixing of several types of raw materials can be a strategy to obtain more optimal physical properties (Wahyudi et al., 2018, 2020).

One of the non-food raw materials that has great potential for biodiesel production is nyamplung oil (Calophyllum inophyllum), which contains long-chain unsaturated fatty acids, especially C18:1, C18:2, and C20:4 (Wahyudi et al., 2021). However, biodiesel from nyamplung oil tends to have a high viscosity and relatively lower calorific value (Che Hamzah et al., 2020). To improve the quality of the biodiesel, it is mixed with other ingredients such as used cooking oil or biodiesel from palm oil which has a higher composition of saturated fatty acids and a shorter carbon chain (Wahyudi & Krisdiyanto, 2022).

Several previous studies have shown that mixing biodiesel from different materials can result in improved physical properties such as decreased viscosity and increased calorific value (Agarwal & Agarwal, 2007; Mariono et al., 2023; Sasongko, 2019). For example, Wahyudi et al. (2021) reported that the mixing of biodiesel from nyamplung and palm oil produced biodiesel with lower viscosity and higher calorific value as the composition of palm oil increased (Wahyudi et al., 2021). Meanwhile, Wahyudi and Krisdiyanto (2022) showed that mixing jatropha biodiesel with used cooking oil produced a significant correlative relationship between density, viscosity, flash point, and calorific value (Wahyudi & Krisdiyanto, 2022).

The characterization of biodiesel is not only limited to the measurement of individual values such as density or viscosity, but it is also important to know the relationship between these parameters. This is important because the physical properties of the fuel affect each other in the combustion process within the engine. For example, high viscosity will affect the spray angle and atomization quality, while density will affect the mass of the injected fuel (Agarwal & Agarwal, 2007; Hoekman et al., 2012). By understanding the correlation between these properties, the formulation of the biodiesel mixture can be optimized to suit the performance needs of diesel engines.

This study aims to analyze the correlation between several main physical properties of biodiesel, namely density, viscosity, calorific value, and flash point, in nyamplung-based biodiesel blends. This study continues and expands on the approach of Wahyudi et al. (2022), focusing on biodiesel produced from local resources and different feedstock blending strategies (Wahyudi & Krisdiyanto, 2022). The correlation between these parameters is evaluated using a linear regression approach, so that a quantitative understanding of the effect of changes in one parameter on other parameters is obtained.

Despite numerous studies on the physical properties of biodiesel derived from various feedstocks, including jatropha, soybean, and used cooking oil, limited research specifically focuses on the interrelationship between the physical properties of biodiesel blends based on nyamplung oil (Calophyllum inophyllum) and palm oil. While previous works have addressed the individual characteristics such as density, viscosity, flash point, or calorific value, there is a lack of comprehensive analysis examining the quantitative correlations among these key parameters in nyamplung-palm biodiesel blends. This gap hinders the optimization of blend formulations tailored for enhanced engine performance and fuel safety, particularly when leveraging local, non-food feedstocks like nyamplung oil, which possesses a unique fatty acid profile distinct from common biodiesel sources.

This study uniquely contributes to the biodiesel literature by systematically analyzing the correlations between the critical physical parameters—density, viscosity, flash point, and calorific value—in biodiesel blends derived from nyamplung oil and palm oil. By employing a linear regression approach to quantify the strength and nature of these relationships, this research elucidates how the fatty acid composition, particularly the presence of long-chain unsaturated fatty acids in nyamplung oil, influences the physical behavior and energy content of the fuel blends. The findings advance the understanding of how blending strategies can balance fuel safety (flash point), engine compatibility (viscosity and density), and energy efficiency (calorific value), offering practical insights for optimizing biodiesel formulation using local resources.

The primary objective of this research is to investigate the correlation among key physical properties—density, viscosity, flash point, and calorific value—of biodiesel blends produced from nyamplung oil and palm oil. This study aims to quantitatively characterize how variations in blend composition affect these interrelated parameters, thereby providing a scientific basis for optimizing biodiesel blends that maximize performance and safety for diesel engine applications.

The results of this study provide critical insights for biodiesel producers, fuel formulators, and policymakers interested in renewable energy development, especially in regions with abundant nyamplung resources. Understanding the interplay between physical properties facilitates the design of biodiesel blends that meet industry standards for combustion efficiency, storage safety, and environmental performance. This research supports the advancement of sustainable energy solutions by promoting the use of non-food feedstocks and enabling the creation of biodiesel with improved functional characteristics, ultimately contributing to energy security, environmental protection, and economic development.

MATERIALS AND METHODS

This research is carried out through several main stages systematically, starting from the preparation of raw materials, the biodiesel production process, mixing, to testing and data analysis. The first stage is the collection and characterization of raw materials in the form of nyamplung oil and palm oil. Each raw material then goes through a pretreatment and esterification process to lower the level of free fatty acids, followed by a transesterification process using methanol and alkaline catalysts (KOH) to produce pure biodiesel. After the purification process through washing and drying, both types of biodiesel are mixed with various compositions (1:9 to 9:1) using a heated mixer. The resulting biodiesel mixture is then tested for its physical properties which include density, kinematic viscosity, flash point, and calorific value. Furthermore, the test results data were analyzed using the linear regression method to evaluate the relationship between physical parameters. This stage is designed to identify the effect of the composition of the mixture on the quality of biodiesel and understand the relationship between the physical properties of the fuel produced (Wahyudi et al., 2021).

Material

The main ingredients used in this study are nyamplung oil (Calophyllum inophyllum) and palm oil. Nyamplung oil was chosen because it is a non-food raw material with a high content of unsaturated fatty acids, while palm oil is a biodiesel raw material whose production is quite abundant (Susanto, 2020).

Biodiesel Production Process

The oil goes through the pretreatment stage because it has a free fatty acid (FFA) content of more than 2%. This stage is carried out through an esterification process using 22.5% methanol to the volume of oil and a H_2SO_4 catalyst of 0.5%, at 60°C for 60 minutes with constant stirring (Wahyudi et al., 2021).

After the esterification process, a separate transesterification process is carried out for each oil. Transesterification is carried out by reacting the oil with methanol (15% of the oil volume) and KOH catalyst (1% of the oil volume) at 60°C for 60 minutes. After the reaction process is complete, the mixture is deposited for ±8 hours to separate the glycerol from the biodiesel.

The next stage is the washing of the biodiesel using hot water (>65°C) to remove the remaining catalysts and other impurities, followed by drying at 100°C for 10 minutes. The biodiesel resulting from this process is then mixed with a composition of 1:9, 2:8, 3:7 and so on until 9:1. The biodiesel mixing process is carried out using a heating device and a mixer with the temperature maintained at 60°C for 60 minutes to produce optimal homogenization.

Testing of the physical properties of the fuel includes measurements of density, kinematic viscosity, flash point, and calorific value. Density is measured by the gravimetric method, which is by measuring the mass of biodiesel in a certain volume, at a temperature of 40°C. Kinematic viscosity is measured using the NDJ-8S digital viscometer at 40°C to obtain viscosity values according to the ASTM D445 standard. The flash point is measured using the Cleveland Open Cup method, which describes the minimum temperature of the fuel to produce flammable vapors in the open atmosphere. The calorific value was measured using the Parr 6050 calorimeter bomb to determine the total combustion energy per unit of fuel mass (Wahyudi et al., 2020).

The test results were analyzed using a simple linear regression method to identify the correlation between the physical parameters of biodiesel, namely between density, viscosity, flash point, and calorific value. Each linear relationship is represented by a regression equation and a coefficient of determination (R^2) to show the strength of the relationship between variables. A value of R^2 close to 1 indicates that the regression model is able to explain most of the variability in the data.

RESULTS AND DISCUSSION

The fatty acid composition of nyamplung oil and palm oil is presented in Table 1. There are quite significant differences in terms of the type and distribution of saturated and unsaturated fatty acid levels. Palm oil is dominated by saturated fatty acids, especially methyl palmitic (C16:0) at 35.27%, while nyamplung oil contains only 11.67% C16:0. In contrast, nyamplung oil contains a higher proportion of long-chain unsaturated fatty acids such as methyl linoleic (C18:2) at 16.3%, methyl eicosatetraenoate (C20:4) at 10.12%, and cis-9-oleic methyl ester (C18:1) at 36.59%. The high C20:4 content of nyamplung oil reflects a greater level of unsaturation than palm oil, which contains only 0.4% C20:4. This profile shows that nyamplung oil has a more complex fatty acid structure and tends to produce biodiesel with higher viscosity and lower oxidative stability (Che Hamzah et al., 2020).

This difference in the structure of fatty acids has direct implications for the physical properties of the biodiesel produced. The high saturated fatty acid content in palm oil contributes to lower viscosity, lower flash point, as well as higher calorific values, as saturated molecules are more stable and flammable (Hoekman et al., 2012). On the other hand, the presence of long-chain unsaturated fatty acids in nyamplung oil increases the density and viscosity of biodiesel, as well as lowers the calorific value and increases the flash point, due to the presence of double bonds that affect the thermal properties and volatility of the fuel (Wahyudi et al., 2021).

Table 1. Fatty acid levels in nyamplung oil and palm oil

Fatty acid	**Fatty acid levels (%)**	
	Nyamplung Oil	**Palm oil**
Methyl Butyrate (C4:0)	6.24	1.21
Methyl Palmitate (C16:0)	11.67	35.27
Methyl Octadecanoate (C18:0)	14.3	3.84
Cis-9-Oleic Methyl Ester (C18:1)	36.59	43.8
Methyl Linoleate (C18:2)	16.3	12.51
Linolelaidic Acid Methyl Ester (C18:2)	0.52	<0,1
gamma-Linolenic acid methyl ester (C18:3)	1.99	0.33
Methyl Lenolenate (C18:3)	2.27	0.26
M Cis-5,8,11,14- Eicosatetraenoic (C20:4)	10.12	0.4

The physical properties of the nyamplung and palm biodiesel mixtures including density, viscosity, calorific value and flash point are presented in Table 2. The test results showed that increasing the biodiesel fraction of nyamplung oil consistently increased the density and viscosity of the biodiesel mixture. The density increased from 856.99 kg/m^3 at 0:10 (100% palm) composition to 914.75 kg/m^3 at 10:0 (100% nyamplung). The same thing also happens with viscosity, from 5.13 cSt to 27.15 cSt. This increase can be explained by the more dominant content of long-chain unsaturated fatty acids in nyamplung oils, such as C20:4 and C18:2, which cause the molecular structure of biodiesel to become more complex and heavier (Hoekman et al., 2012; Wahyudi et al., 2021). High viscosity impacts the fuel flow resistance, affecting fuel mist formation and combustion efficiency within the combustion chamber (Agarwal & Agarwal, 2007).

Table 2. Physical properties of biodiesel mixture Nyamplung - palm oil

Comparison of Nyamplung Biodiesel : Palm Oil	**Density (kg/m^3)**	**Viscosity (cSt)**	**Flash Point (° C)**	**Calorific Value (MJ/kg)**
0:10	856.99	5.13	182.6	9547.88
1:9	860.58	5.58	182.23	9472.40
2:8	872.06	6.35	179.83	9473.53
3:7	874.17	7.24	181.00	9412.22
4:6	877.30	8.36	188.37	9419.79
5:5	885.92	10.54	190.70	9398.73
6:4	890.97	10.92	204.47	9378.35
7:3	897.64	13.52	210.00	9340.82
8:2	903.92	19.03	210.33	9271.44
9:1	912.49	18.63	217.33	9252.62
10:0	914.75	27.15	239.33	9217.31

Meanwhile, flash point values show a significant increasing trend as the composition of nyamplung oil increases. The flash point rises from 182.6°C at 0:10 mix to 239.33°C at 10:0. This

indicates that mixtures with higher nyamplung content are safer against the risk of fire during storage, as higher temperatures are required to evaporate sufficient amounts of fuel for ignition (Wahyudi et al., 2021). This higher flash point is related to the content of heavy and unsaturated compounds in nyamplung which reduces fuel volatility (Wahyudi & Krisdiyanto, 2022). This increase also supports the previous trend that showed a positive correlation between viscosity and flash points, as compounds with high viscosity typically also have low volatility.
The calorific value shows a downward trend as the nyamplung fraction increases, from 9547.88 MJ/kg at 0:10 to 9217.31 MJ/kg at 10:0. This is due to the high oxygen content in unsaturated fatty acids of nyamplung oil which reduces the ratio of C:H:O and fuel energy density (Hoekman et al., 2012; Wahyudi & Krisdiyanto, 2022). Lower calorific values can have an impact on the reduction of the engine's energy output if the injection volume is fixed. Therefore, although biodiesel has advantages in terms of storage safety due to its high flash point, the decrease in calorific value and increased viscosity need to be compensated through adjustment of the composition of the mixture to still meet optimal performance in diesel engine applications. Blending strategies like this are important to balance thermal efficiency and fuel safety characteristics.

Correlation between Density and Viscosity

Figure 1 shows the linear relationship between the density and kinematic viscosity of the nyamplung oil-based biodiesel mixture and palm oil. The regression equations obtained are:

$$\text{Viskositas} = 0{,}3272 \times \text{Densitas} - 277{,}92 \quad (1)$$

with a coefficient of determination value (R^2) of 0.8834, which indicates a very strong correlative relationship. This indicates that the viscosity of biodiesel is significantly affected by the density of the fuel. High density values are usually associated with the length of the carbon chain and the high level of unsaturation of the constituent fatty acids, resulting in a higher viscosity as well (Ennetta et al., 2022; Hoang, 2021).

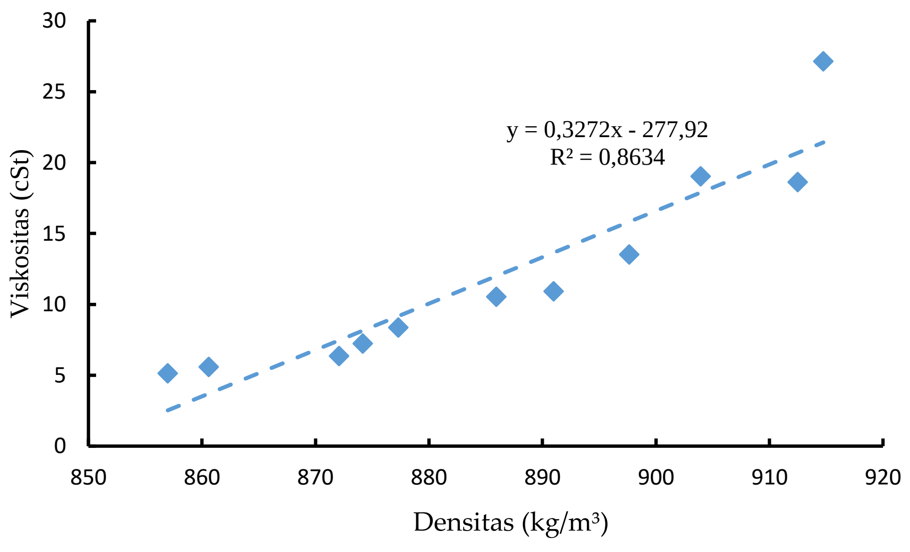


Figure 1. Correlation between density and viscosity

This phenomenon is in line with the results of research by Wahyudi et al. (2022) which show that an increase in density in the mixture of jatropha biodiesel and used cooking oil also causes an increase in viscosity (Wahyudi & Krisdiyanto, 2022). This can be explained by the molecular structure of unsaturated fatty acids in nyamplung oil that dominate the mixture and contribute to the simultaneous increase in density and viscosity values (Kumbhar et al., 2022; Lanjekar & Deshmukh, 2016; Maksom et al., 2020).

Correlation between Density and Flash Point

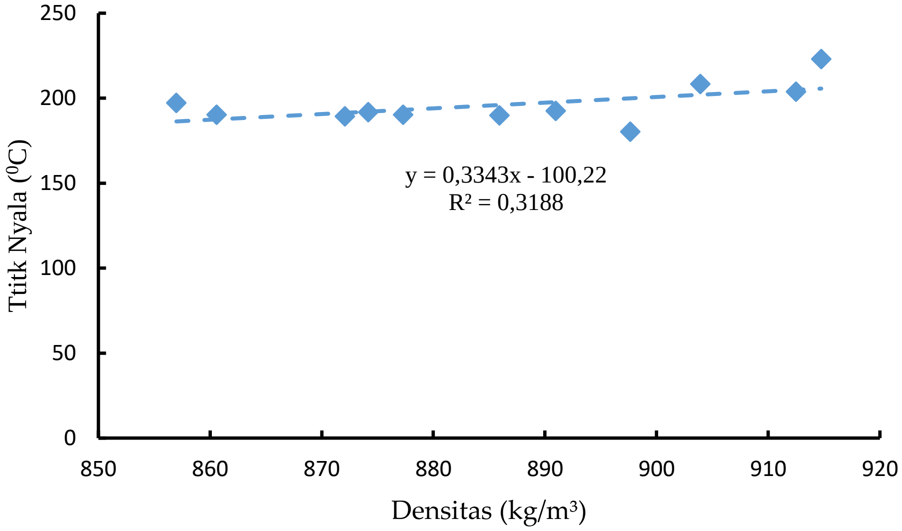


Figure 2. Correlation between density and flash point

Figure 2 shows the correlation between density and biodiesel flash point. The regression equations obtained are:

$$\text{Titik Nyala} = 0{,}3343 \times \text{Densitas} - 100{,}22 \quad (2)$$

with a coefficient of determination (R^2) of 0.3188. The relatively low R^2 value indicates that despite the positive tendency, the relationship between density and flash point is not very strong. This suggests that other factors such as fatty acid type, volatility level, and mild compound content have a dominant influence on the flash point (Carareto et al., 2012).

Flash points are an indicator of fuel storage safety because they indicate the minimum temperature to produce flammable vapors. High density can be associated with larger, less volatile molecules, thus increasing the flash point (Wahyudi & Krisdiyanto, 2022). However, due to the multitude of factors that affect the flash point, a simple linear relationship is not sufficient to explain the variability of these parameters thoroughly. Research by Carareto et al. (2012) also confirms that chemical structures, especially the length and branches of the carbon chain, contribute significantly to the fuel flash point (Carareto et al., 2012).

Correlation between Density and Calorific Value

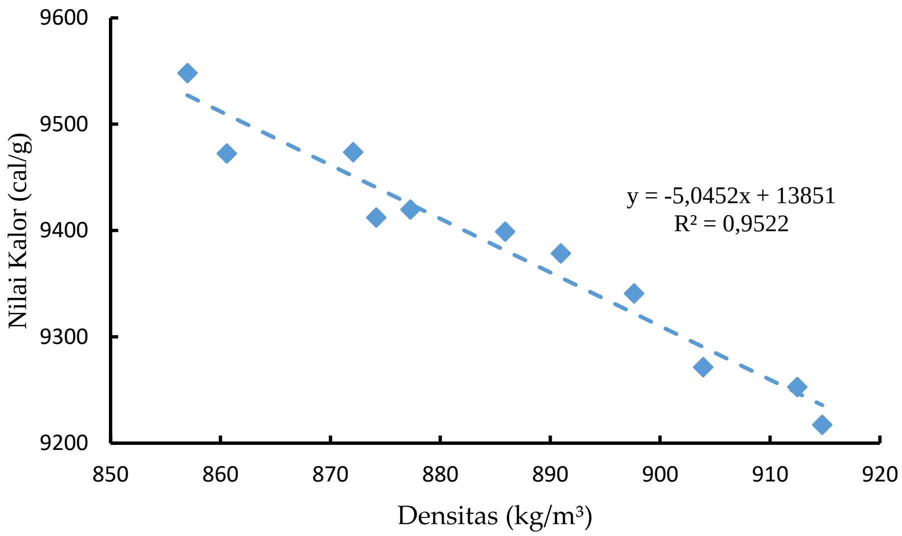


Figure 3. Correlation between density and calorific value

Figure 3 shows the negative relationship between density and heating value. The regression equations obtained are:

$$\text{Calorific Value} = -5{,}0452 \times \text{Densitas} + 13851 \qquad (3)$$

with an R^2 value of 0.9522, indicating that the relationship between these two parameters is very strong and consistent. The lower calorific value in high-density biodiesel is most likely due to the higher oxygen content and high levels of unsaturation in the fatty acid molecules (Hoekman et al., 2012; Pawar et al., 2023).

This negative relationship is consistent with the findings of Wahyudi and Krisdiyanto (2022) which show that an increase in fuel density decreases the calorific value because the energy content per unit mass decreases due to an increase in the ratio of oxygen to carbon (Wahyudi & Krisdiyanto, 2022). In addition, the greater carbon chain length in fatty acids such as C20:4 in nyamplung oil also reduces the calorific value as it decreases combustion efficiency. Therefore, the formulation of biodiesel blends needs to consider the balance between density and calorific value to maximize energy output per volume of fuel.

Correlation between Viscosity and Flash Point

Figure 4 shows the positive relationship between viscosity and flash point, with regression equations:

$$\text{Titik Nyala} = 2{,}6582 \times \text{Viskositas} + 166{,}74 \qquad (4)$$

and an R^2 value of 0.9343, which indicates a very strong correlation. Increased viscosity is usually associated with a long carbon chain and a high level of unsaturation, which causes the fuel to be less volatile and requires higher temperatures to produce combustible vapors (Rodrigues Jr et al., 2006; Tamilselvan et al., 2020).

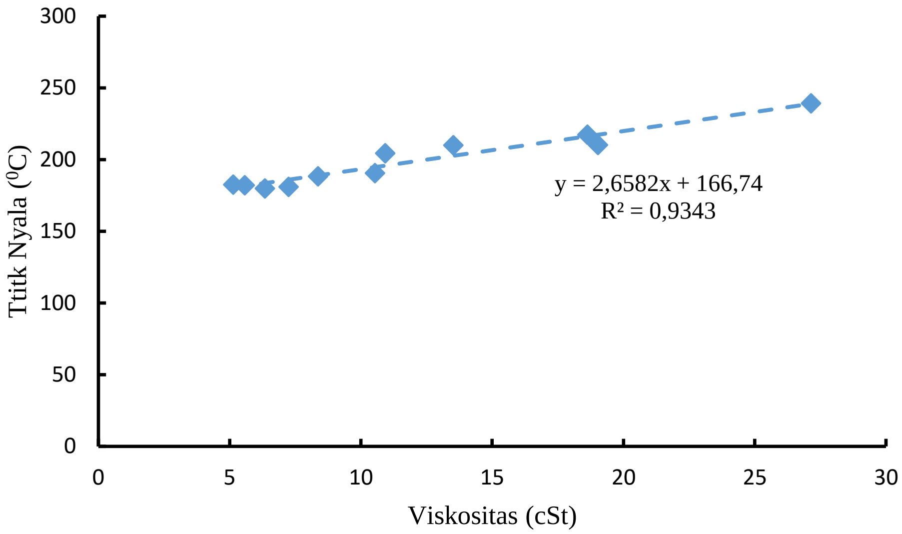
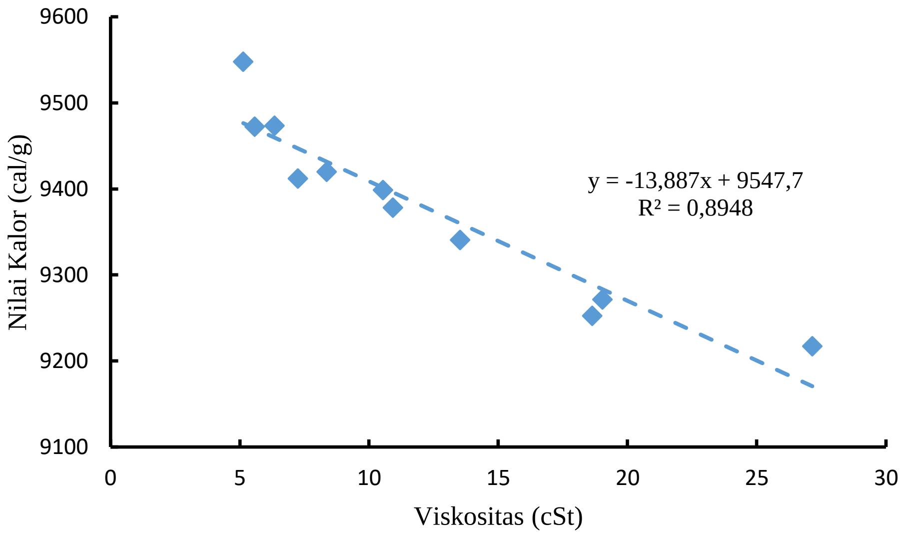


Figure 4. Correlation between kinematic viscosity and flash point

This correlation was also found in previous studies on a mixture of jatropha and used cooking oil, where higher viscosity led to higher flash points (Wahyudi & Krisdiyanto, 2022). This phenomenon implies that high-viscosity fuels tend to be safer for storage, although they have challenges in the process of injecting and atomizing fuel in diesel engines.

Correlation between Viscosity and Calorific Value



Gambar 5. Korelasi antara viskositas kinematik dan nilai kalor.

Gambar 5 menunjukkan hubungan negatif antara viskositas dan nilai kalor, dengan persamaan regresi:

$$\text{Nilai kalor} = -13{,}887 \times \text{Viskositas} + 9547{,}7 \quad (5)$$

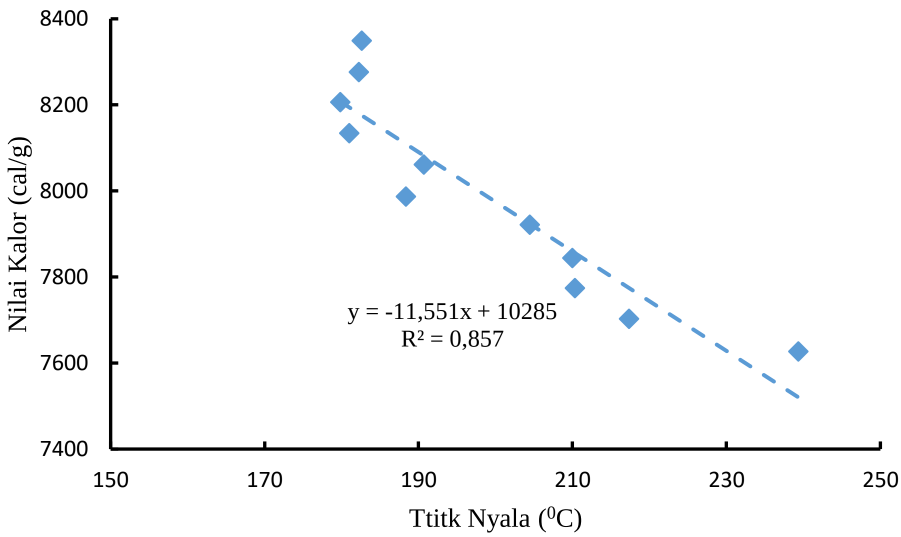
and the R^2 value of 0.8948. This relationship explains that the higher the viscosity, the lower the calorific value of biodiesel. This is due to the fact that high viscosity is often associated with complex fatty acid structures and high oxygen content, which decreases energy efficiency during

combustion (Hoekman et al., 2012).
Previous studies have also reported similar trends, including Wahyudi et al. (2022), who stated that increased viscosity due to unsaturated fatty acids reduces the energy content of biodiesel (Wahyudi & Krisdiyanto, 2022). This shows that viscosity not only affects flow and fuel injection characteristics, but also has a direct impact on thermal performance through a reduction in calorific value. Thus, biodiesel viscosity optimization must pay attention to its effect on calorific value as an indicator of energy efficiency.

Correlation between Flash Point and Calorific Value
Figure 6 illustrates the negative relationship between the flash point and the calorific value with the regression equation:

$$\text{Nilai Kalor} = -11{,}551\text{xTitik Nyala} + 10285 \quad (6)$$

dan nilai R^2 sebesar 0,8570. Korelasi ini menunjukkan bahwa bahan bakar dengan titik nyala tinggi cenderung memiliki nilai kalor yang lebih rendah. Hal ini dapat dikaitkan dengan struktur molekul yang kompleks dan kandungan oksigen yang tinggi dalam biodiesel berbasis nyamplung (Hoekman et al., 2012).



Gambar 6. Korelasi antara nilai kalor dan titik nyala

An increase in the flash point in high-viscosity fuels indicates a less volatile content of heavy compounds, thus also contributing to a decrease in calorific values (Wahyudi & Krisdiyanto, 2022). Although a high flash point is an advantage in terms of safety, a decrease in heat value can have an impact on a decrease in fuel efficiency in energy generation.

CONCLUSIONS

This study demonstrates a significant relationship between the physical parameters of biodiesel blends derived from nyamplung oil and palm oil. Statistical analysis revealed a strong positive correlation between density and viscosity (R^2 = 0.8834), while the correlation between density and flash point was less pronounced (R^2 = 0.3188). Notably, a very strong negative correlation was observed between density and calorific value (R^2 = 0.9522), indicating that increased density corresponds to decreased fuel energy efficiency. Additionally, viscosity showed a very strong positive correlation with flash point (R^2 = 0.9343) and a strong negative correlation with calorific value (R^2 = 0.8948), highlighting its influence on fuel flow characteristics as well as thermal performance and storage safety. The flash point also correlated negatively with calorific value (R^2 = 0.8570), confirming that heavier, less volatile compounds yield lower energy content. These findings reinforce previous research that the chemical structure of fatty acids, especially carbon chain length and degree of unsaturation, critically affects the physical and energetic properties of biodiesel. Understanding these interrelationships is vital for formulating biodiesel blends that optimize engine performance, energy efficiency, and storage safety. For future research, it is recommended to investigate the impact of these physical parameters on engine emission characteristics and long-term engine durability, as well as explore the effects of blending with other local feedstocks to broaden the applicability and sustainability of biodiesel formulations.

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