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Research Paper

Reducing Exhaust Emissions from Palm Oil Biodiesel Diesel Engines by Adding Hydrogen Gas

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Abstract

The application of hydrogen enrichment of palm oil-based biodiesel in a compression ignition engine was examined in this work. Synthesized from crude palm oil (CPO), biodiesel was first fed into a single-cylinder diesel engine. The intake manifold received hydrogen gas at flows of 2.5 lpm, 5 lpm, 7.5 lpm, and 10 lpm. Operating at a constant speed of 2,000 rpm, the single-cylinder, direct-injection diesel engine used The aim of this work is to assess the performance and emissions of a diesel engine utilizing hydrogen gas and CPO biodiesel fuels. This work examined engine performance and exhaust emissions using smoke emissions, exhaust temperature, power, thermal efficiency, and fuel economy. Addition of hydrogen improved emissions and performance. Optimal engine performance was achieved by adding 2.5 lpm of hydrogen, which resulted in a 20.12% increase in brake thermal efficiency (BTE) and a 27.57% reduction in fuel consumption compared to biodiesel. The addition of hydrogen gas has a positive impact on exhaust emissions (HC, CO_2, and smoke opacity), but has a negative impact on NO emissions. At elevated loads of 2.5 lpm hydrogen flow, emissions measured were 40.00 ppm, 0.04%, 4.20%, and 44.20%, respectively, alongside a 45.72% increase in NO emissions. Including hydrogen gas improves the diesel engines running on biodiesel's performance and exhaust pollutants.

Keywords: Dual fuel, CPO biodiesel, Exhaust emissions, exhaust temperature, Engine performance

1. Introduction

The potential of biodiesel has been assessed as an alternative to diesel oil by government regulation No. 12/2015, which requires a mixture of 30% biodiesel with diesel oil from 2020 to 2025 [1]. Biodiesel is a renewable fuel derived from organic plant components, specifically palm oil utilized in diesel engines, either as a blend of diesel fuel or pure biodiesel fuel [2]–[7]. Biodiesel derived from crude palm oil (CPO) is widely recognized for its environmentally sustainable characteristics [8]–[10]. The oxygen content in biodiesel of around 9-12% provides various advantages, such as reducing smoke emissions, carbon monoxide (CO), hydrocarbons (HC), and exhaust gas temperatures [11]–[13]. A study by Bari and Hossain [14] shows that using CPO as fuel in diesel engines, compared to traditional diesel fuel, can reduce exhaust emissions of CO, CO_2, and HC by up to 50%. One advantage of biodiesel is its higher cetane number compared to diesel fuel [12], [15]–[17]. A higher cetane number shortens the ignition delay time, thereby improving the combustion efficiency of diesel engines. This also allows the engine to run more smoothly and with less delay [18], [19]. Additionally, biodiesel derived from CPO is considered environmentally sustainable [20].

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The use of biodiesel negatively affects the performance of diesel engines. According to Gad et al. [11], it has been discovered that incorporating biodiesel into a system can decrease power and average effective pressure, primarily because of its low calorific value. Furthermore, the engine has detrimental effects when biodiesel is used for an extended period without any modifications, mostly due to the elevated viscosity, reduced volatility, and reactive nature of unsaturated hydrocarbon chains [21]. In addition, the viscosity value also affects higher BSFC, longer combustion duration, BTE, HRR, and decreased engine peak pressure [11], [22]–[25]. To enhance the subpar performance of diesel engines when utilizing biodiesel fuel, it is possible to ameliorate the situation by introducing minute quantities of hydrogen into the intake manifold. Hydrogen fuel has several benefits, such as its flammability, low density, and high calorific value [26]–[31]. Diesel Dual Fuel (DDF) technology plays a crucial role in diesel engines by enabling the use of two types of fuel. DDF engines are specially designed to operate with a combination of fuels, using biodiesel as the pilot fuel and hydrogen as the main fuel.

Several studies have highlighted how to reduce emissions and how to improve diesel engine performance with DDF systems. Yilmaz et al. [32] have conducted research on a 4-cylinder diesel engine. The findings demonstrated that the incorporation of HHO leads to a notable enhancement in engine torque, with an average increase of 19.1%. Emission reductions of 13, 5, and 14 percent, respectively, in CO, HC, and SFC emission types. Boopathi et al. [26] found that a DDF engine running on palm oil biodiesel increased NOx emissions by 16.67% at low load when hydrogen flow rates were varied by 5 lpm and 10 lpm. According to studies by Karthic et al. [33], using biodiesel made from Madhuca Longifolia in dual-fuel diesel engines raises the temperature of the exhaust gas. This is because as hydrogen gas burns, it releases more energy. Studies by Sivabalakrishnan and colleagues [34]. When hydrogen and biodiesel are combined in a diesel engine, knocking may happen. This is because hydrogen has a lower ignition energy, a wider range of flammability, and a shorter flame propagation distance. Research by Nag et al. [35] showed that when hydrogen makes up 20% of the hydrogen energy share (HES), the likelihood of engine knocking increases significantly at 75% load. This is attributed to elevated cylinder temperatures, which create localized hot spots and heighten the risk of knocking. Similarly, Uludamar et al. [36] investigated the effects of combining hydrogen fuel with biodiesel on noise, engine vibrations, and pollutant emissions. Their findings revealed that the type of biodiesel used played a crucial role in reducing engine noise, vibrations, and emissions.

Previous studies have explored the effects of combining biodiesel and hydrogen gas in single-cylinder diesel engines [12], [24], [37]–[39]. These studies show that integrating hydrogen into the combustion process improves engine performance and reduces exhaust emissions. The quality of biodiesel is significantly influenced by the raw materials used in its production. Therefore, our present study investigates the impact of blending hydrogen gas with biodiesel derived from palm oil on diesel engine performance and combustion characteristics, focusing on efficiency and emissions. Despite Indonesia being the largest global producer of palm oil, research on the use of palm-based biodiesel in diesel engines remains limited. In contrast, extensive studies have been conducted on biodiesel-diesel blends. This research evaluates the performance of a single-cylinder diesel engine powered by CPO and hydrogen blend, aiming to optimize performance and reduce emissions by varying hydrogen input.

2. Material and Methods

The study utilized a single-cylinder diesel engine with a maximum power of 6.2 kW at 2000 rpm. The electric generator serves to evaluate the engine's performance through the application of an incandescent lamp load. The power load for each lamp is 500 watts, while the range of power load utilized in this study spans from 1000 watts to 4000 watts. The analysis of carbon emissions from smoke employs a smoke meter. The assessment of biodiesel fuel consumption requires a stopwatch to measure the time taken for 25 ml of fuel to be exhausted. A digital flowmeter quantifies hydrogen gas, measuring flow rates from 0 to 10 liters per minute. The procedure entails the transfer of hydrogen gas from a cylinder at 150 bar to 1 bar through the regulator.

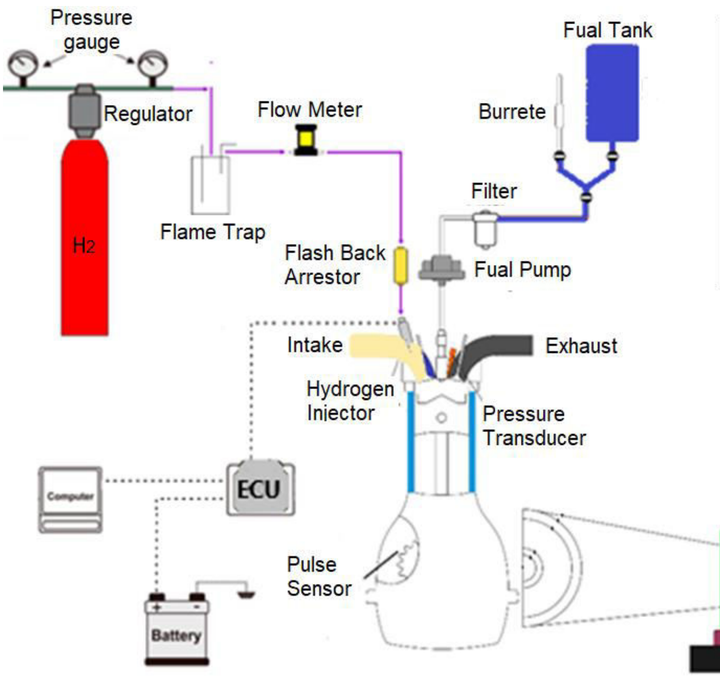
Hydrogen gas is mixed with air before entering the combustion chamber, whereas biodiesel is sent directly into the combustion chamber. The analysis of carbon emissions from smoke employs a smoke meter [40]. The experimental equipment scheme is presented in **Figure 1**. This experiment utilized hydrogen gas and biodiesel generated from crude palm oil (CPO) as fuel. CPO biodiesel was supplied by Wilmar Nabati Indonesia Company, while hydrogen gas was provided by Samator Company. Fuel specifications are presented in **Table 1** and **Table 2**, respectively.

3. Results and Discussion

This study investigates the impact of using CPO biodiesel (B100) combined with hydrogen gas on the performance and emissions of dual-fuel diesel engines. The analysis of combustion emissions includes nitrogen oxides (NO), hydrocarbons (HC), smoke, carbon dioxide (CO_2), and exhaust gas temperature (EGT). Engine performance is evaluated based on energy output, thermal efficiency, and specific fuel consumption.

3.1. *Engine Emissions*

Engine NO emissions are shown in **Figure 2a**. The addition of hydrogen to biodiesel affects NO emissions increasing with increasing engine load. At low loads starting from 1-3 kW, NO emissions are still low compared to biodiesel and diesel, because the combustion chamber temperature has not increased. However, compared to single fuel, namely biodiesel, the increase was 24.48% at a load of 3 kW with a hydrogen flow of 10 lpm.



Model	DI 800 H
Type	Single-cylinder, four stroke
Combustion system	Direct injection
Bore x stroke	82 x 78 mm
Displacement	411 cc
Maximum power	7 HP (5.22 kW)/2200 rpm
Continous power	6 HP (4.47 kW)/2000 rpm
Compresion Ratio	18:1
Pilot injection timing	13 °BTDC
Cooling system	Hopper

Figure 1. Schematic of testing equipment

Table 1. CPO biodiesel and hydrogen fuel specifications

No	Properties	CPO Biodiesel	Hydrogen
1	Density at 15 °C (Kg/m³)	875	0.085
2	Kinematic Viscosity 40°C (mm²/s (cSt))	4.5	0
3	Cetane Number (Min)	56.7	5-10
4	Flash Point (°C, Min)	140	
5	Fog Point (°C, Max)	15.4	
6	Lower Heat Value (kJ/kg)	39.910	119.810
7	Auto Ignition Temperature (°C)	>101	585
8	Stoichiometric Air-Fuel Ratio	12.5	34.3

Table 2. Testing tool specifications

Flowmeter gase H_2		Gas Analyzer		Smoke opacity meter	
Type	MF 5712	Merk	Hesbone	Merk	Heshbone
Flow range	0-200 SLPM	Type	HG-520	Type	HD-410
Accuracy	+/- (2.0+0.5FS)	CO Measurement range	0 – 9.99% with 0.01% resolution	Measurement range	0 – 100%
Repeatability	+/- 0.5%	HC Measurement range	0 – 999 ppm with 1 ppm resolution	Precision	+/- 1%
Respone Time	< 2 sec	CO_2 Measurement range	0 – 20% with 0.01% resolution	Power supply	110/220V AC 50/60 Hz
Max Pressure	< 0.8 MPa	O_2 Measurement range	0 – 25% with 0.01% resolution	-	-
Working Temperature	-10 ~ 55 °C	Power supply	110/220/240 V AC 50/60 Hz	-	-

Sequentially, the increase in NO emissions at high loads with diesel, biodiesel, BH2.5, BH5, BH7.5, and BH10 fuels is 75 ppm, 103 ppm, 191 ppm, 170 ppm, 180 ppm, and 199 ppm, respectively. During the compression stroke, the engine's peak temperatures and pressures rise, which causes an increase in NO emissions. The same trend has been observed by researchers [41], [42].

Figure 2b illustrates a significant reduction in HC emissions with the addition of hydrogen gas. This occurs because the combustion temperature rises, leading to a faster ignition rate, more complete fuel combustion, and an expanded combustion area [43]. The modulation of the hydrogen gas addition flow rate can diminish hydrocarbon emissions in the dual fuel system due to the accelerated combustion velocity of hydrogen, resulting in reduced unburned fuel. Good combustion is combustion that can burn all the fuel that has been entered into the combustion chamber [44]. Moreover, the addition of hydrogen raises the combustion temperature, as demonstrated by data showing higher exhaust gas temperatures with increased hydrogen content. The lowest HC emissions occur in the variation of 10 lpm hydrogen gas with a value of 22 ppm or a 75% decrease from the single fuel system.

Figure 2c depicts smoke opacity emissions increasing as the engine load rises. At high loads, the use of diesel and biodiesel fuels results in reduced smoke emissions due to the elevated combustion chamber temperature, which promotes more complete fuel combustion. However, this also leads to higher exhaust gas temperatures. The amount of biodiesel injected into the combustion chamber suggests that it does not burn entirely, as indicated by the increased smoke opacity emissions. This phenomenon can be attributed to the fact that biodiesel, used as a pilot fuel, is part of the long-chain paraffin family, which contributes to higher smoke opacity emissions [41], [42]. The maximum smoke opacity emission occurs on average when the load is 3.5 kW. The dual fuel system exhibits much lower smoke opacity emissions in comparison to the single fuel system. The use of hydrogen reduces the amount of biodiesel fuel entering the combustion chamber, which in turn lowers smoke opacity emissions. The most significant reduction in smoke opacity is achieved at a hydrogen gas flow rate of 10 lpm, as this provides more hydrogen and the highest level of biodiesel substitution. Smoke formation occurs when fuel does not burn completely, which can result from factors such as incomplete combustion, insufficient oxygen, an improper air-fuel mixture in the combustion chamber, or low combustion temperatures [11].

One advantage of using hydrogen gas as a fuel supplement in diesel engines is the reduction of CO_2 emissions [45]. As seen in **Figure 2**d, CO_2 emissions from dual fuels exhibit a declining trend relative to single fuels, such as diesel and biodiesel. The incorporation of hydrogen markedly enhances biodiesel fuel testing due to the oxygen concentration present in biodiesel. According to previous research that mixed biodiesel fuel in diesel engines, CO_2 emissions decreased because hydrogen gas does not contain carbon molecules [46]–[48].

3.2. *Exhaust Gas Temperatur (EGT)*

Figure 3 illustrates the exhaust gas temperature (EGT) for an engine utilizing B100 fuel with variable hydrogen flow rates of 2.5 lpm, 5 lpm, 7.5 lpm, and 10 lpm. The graph depicts the correlation between EGT and various engine load fluctuations. From **Figure 3**, it is elucidated that an elevation in exhaust gas temperature occurs due to heightened load, this is a result of energy being introduced into the combustion chamber to generate engine power, thus amplifying the electrical load. Increasing the fuel quantity in the combustion chamber enhances the input energy, leading to a more significant conversion of energy into heat during combustion [49]. An extremely rich fuel mixture results in a higher volume of unburned fuel during combustion, causing a rise in exhaust gas temperature due to this unburned fuel.

Incorporating hydrogen into the combustion process enhances the input energy. Given the superior calorific value of hydrogen relative to biodiesel, the exhaust gas temperature rises with variations in the hydrogen flow rate. The temperature reaches its peak at a flow rate of 10 liters per minute under a 4000-watt load, achieving a temperature of 411°C. The increase in exhaust gas temperature is ascribed to the hydrogen mixture and the elevated calorific value of hydrogen gas as a fuel [26]. An increase in exhaust gas temperature affects NO emissions.

3.3. *Effective Engine Power*

Figure 4 Displays the effective power statistics of the engine utilizing B100 fuel with hydrogen flow variations of 2.5 lpm, 5 lpm, 7.5 lpm, and 10 lpm. The graph illustrates the effective power in relation to various engine load fluctuations. The

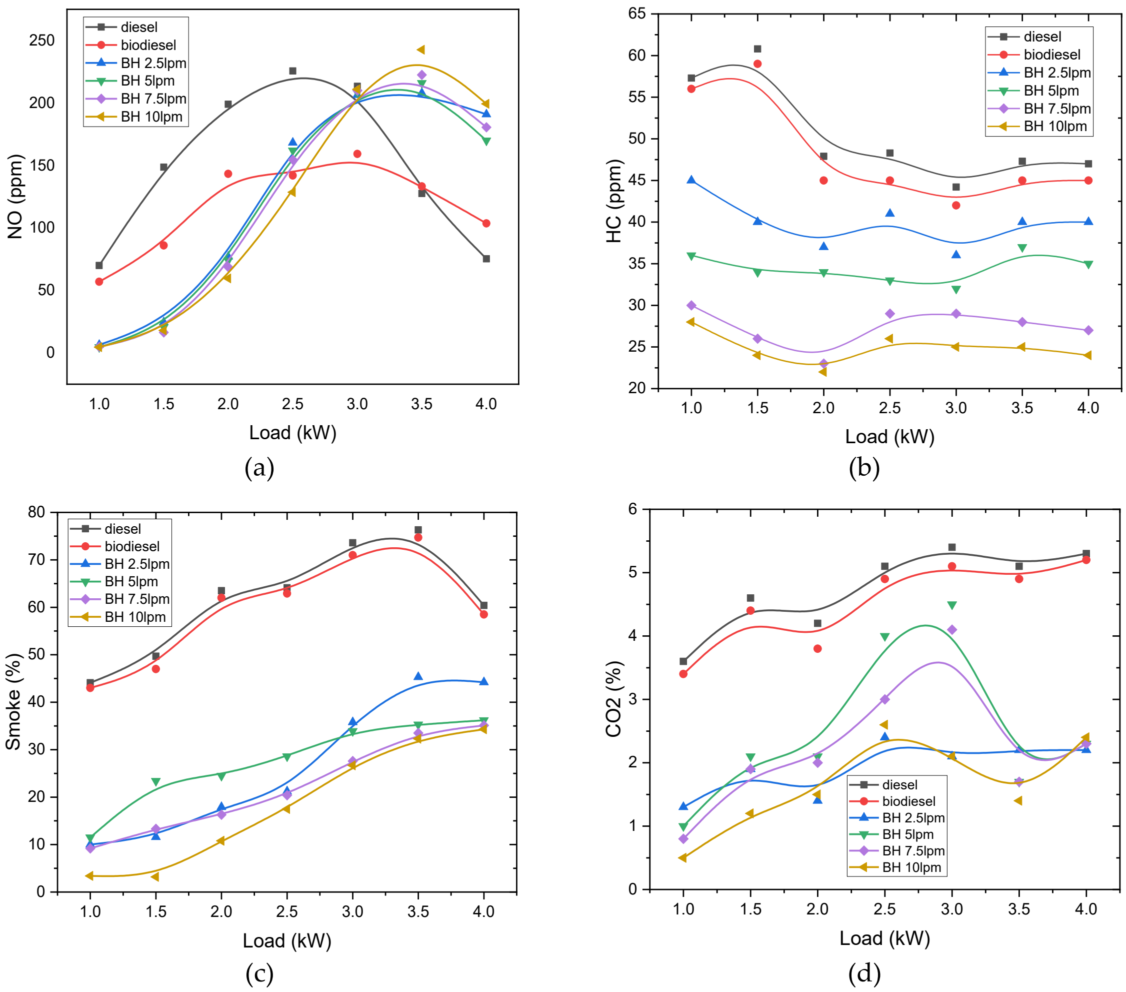


Figure 2. Emissions NO (a), HC (b), Smoke (c), CO_2 (d) on engine load

power variation against different hydrogen flows is shown in **Figure 4**. In comparison to the maximal hydrogen flow in dual-fuel operation, the power output when using single-fuel biodiesel is 0.9% lower. The incorporation of hydrogen as a secondary fuel has led to an increase in engine capacity. As the flow of hydrogen gas increases, the engine produces more power. Another reason is that the higher calorific value of hydrogen gas the flame speed of hydrogen and the combustion that is enhanced by the presence of hydrogen molecules mixed with oxygen can produce high engine power [50]. The addition of a higher hydrogen gas flow causes the effective engine power to increase. The power increase for each fuel is 2.24 kW, 2.28 kW, 2.11 kW, 1.80 kW, 2.27 kW for B100, BH2.5, BH5, BH7.5, and BH10, in that order. A higher calorific value and increased hydrogen flame speed improve combustion and engine output [51], [52].

3.4. *Brake Thermal Efficiency (BTE)*

Figure 5 shows BTE data on an engine with B100 fuel and hydrogen flow rate variations (2.5, 5, 7.5, and 10 lpm). The graph shows BTE against different engine load variations. The variation of diesel thermal efficiency can be seen in **Figure 5**. The introduction of hydrogen results in improved thermal efficiency during diesel engine operation. An important enhancement in thermal efficiency at a high load of 4kW has been noted with a hydrogen concentration of 10 lpm. The increase in thermal efficiency is 11.74%, 13.91%, 17.41%, 17.31%, 15.25%, and 23.32% for diesel, Biodiesel, BH2.5, BH5, BH7.5, and BH10, respectively. Increased hydrogen flow rates result in a significant accumulation of hydrogen gas within the combustion chamber. The enhanced thermal efficiency is a result of the increased volume of pilot fuel injected, leading to a higher number of ignition and combustion points. The observed increase is due to the rapid combustion process, resulting in heat release over a short duration. This heat is not utilized for generating engine power; instead, it dissipates as heat loss to the walls of the combustion chamber [26].

3.5. *Specific fuel consumption (SFC)*

Figure 6 presents the specific fuel consumption (SFC) for the engine running on B100 fuel at various hydrogen flow rates of 2.5 lpm, 5 lpm, 7.5 lpm, and 10 lpm. The graph illustrates the relationship between SFC and different engine load variations. It shows a downward trend in SFC as the hydrogen flow rate increases. Increased combustion chamber temperatures and shorter ignition delays are two of the elements that reduce fuel consumption because they enable the injected fuel to burn more efficiently and convert into engine power. As a result, less fuel is needed to produce the same amount of power, as also explained in the study [50]. Single fuel diesel and B100, as well as dual fuel versions, demonstrate distinct specific fuel consumption values at a load of 4 kW with differing hydrogen gas flow rates. The recorded values are 567.74 gr/kWh, 539.02 gr/kWh, 422.53 gr/kWh, 414.33 gr/kWh, 461.57 gr/kWh, and 290.25 gr/kWh for flow rates of 2.5 lpm, 5 lpm, 7.5 lpm, and 10 lpm, respectively. The image shows that at low loads, higher fuel consumption is required. The lower mixture of hydrogen gas and air leads to inadequate combustion of the biodiesel fuel, resulting in a reduced burning duration.

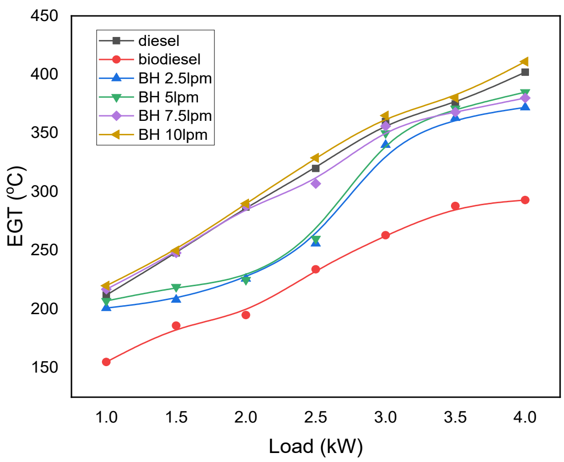


Figure 3. Variation of EGT against engine load

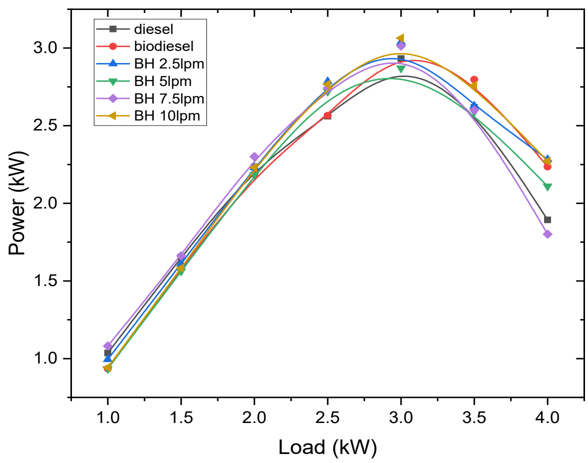


Figure 4. Power against engine load

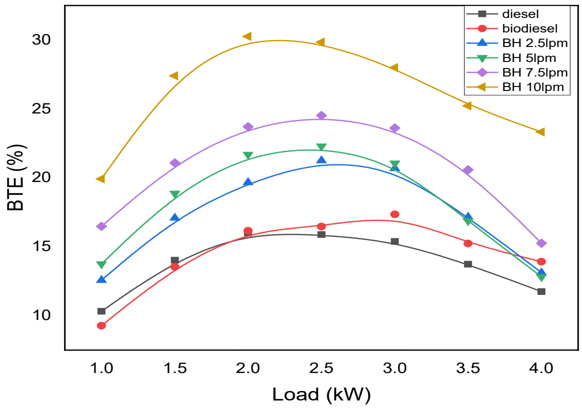


Figure 5. Variation of engine BTE on engine load

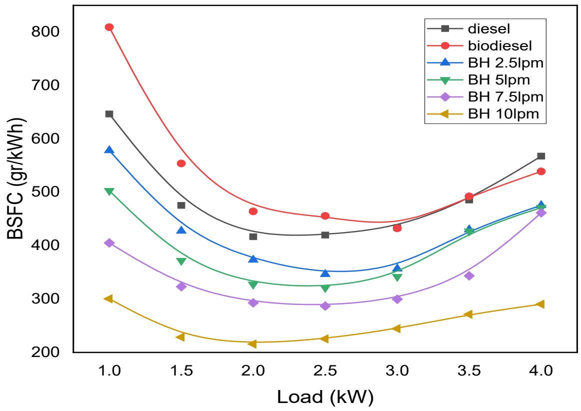


Figure 6. Specific fuel consumption on engine load

Previous studies suggest that knocking can be influenced by the introduction of hydrogen gas, which increases heat release within the combustion chamber [12]. Additionally, hydrogen gas contributes to improved thermal efficiency and higher NO emissions due to its calorific value being three times that of biodiesel [38]. However, this study shows that at low loads, the reaction between hydrogen and biodiesel can reduce NO emissions compared to diesel fuel.

4. Conclusion

This study investigated the effect of hydrogen gas addition on the performance of a single-cylinder diesel engine fueled by CPO biodiesel. As a result, we found that adding hydrogen gas significantly reduced fuel consumption and improved thermal efficiency compared to using pure biodiesel. Specifically, the addition of hydrogen gas at a rate of 10 lpm resulted in a 47.61% reduction in fuel consumption and a 67.64% increase in thermal efficiency. These findings highlight that even a small amount of hydrogen gas can substantially improve the performance of a diesel engine while reducing emissions. This study provides valuable insights for the mechanical engineering discipline, demonstrating the potential of hydrogen gas to improve the efficiency and sustainability of CPO biodiesel-fueled diesel engines.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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