Assessment of hydrogen induction with Juliflora biodiesel as an alternative fuel for CI engines

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Abstract

To address the needs of a growing population and promote sustainability, humanity is shifting towards more eco-friendly lifestyles. Biodiesel offers a renewable alternative derived from natural sources like vegetable oils and animal fats. Its adoption could lead to reduced greenhouse gas emissions, enhanced air quality, improved energy security, and minimized environmental harm from oil spills. Researchers are exploring hydrogen gas as an eco-friendly fuel option, in addition to biodiesel, because of its high energy density. This study examines the performance, combustion, and emission characteristics of a hydrogen port-injection engine fuelled by Juliflora biodiesel. Tests conducted on a Kirloskar TV 1 DI diesel engine utilized various blends of diesel and biodiesel with different hydrogen contents. Hydrogen fuel injection occurred at a 45-degree angle into the engine's intake manifold at rates ranging from 3 to 9 litres per minute, alongside B100 biodiesel blends. The study tracked multiple performance indicators such as fuel consumption and braking effectiveness, alongside emissions of NO, HC, CO, CO_2 and smoke opacity. This study's findings show that boosting the hydrogen induction flow rate alongside Juliflora biodiesel leads to higher brake thermal efficiency and lower specific fuel consumption. However, it also results in increased NO and opacity levels but reduced CO and HC emissions. Additionally, there's an observed rise in in-cylinder pressure and net heat release rate.

Keywords:
Engine, Performance, Emission, Biodiesel, Hydrogen

1. Introduction

Energy serves as a gauge for a nation's economic health, driving advancements in engine technology, with natural resources serving as the bedrock for economic prosperity. India, as a developing nation, heavily relies on its limited reservoirs of crude oil for industrial and transportation needs.[1] The growing disparity between crude oil production and consumption, as warned by various literary and scientific sources, suggests an impending depletion of these resources. The current reserves are inadequate to bridge the energy gap, potentially leading to an energy crisis if left unchecked. To address the escalating demand for crude oil, India resorts to importing a significant portion of its requirements, posing risks of a foreign exchange crisis. Hence, there's an urgent need to prioritize sustainable energy solutions and explore alternative fuel sources to achieve self-sufficiency.[2, 19.]

Diesel engines, favoured for their efficiency and fuel economy, dominate transportation and power generation sectors. However, their emissions of harmful pollutants like particulate matter, carbon monoxide (CO), and nitrogen oxides (NO) pose environmental challenges. India, with over 150 million vehicles on its roads, heavily relies on petroleum products, especially diesel, for various purposes including mobility and agriculture. This reliance exacerbates environmental pollution, particularly in urban areas.[3]

The escalating energy demand, coupled with projected fossil fuel depletion and environmental concerns, underscores the importance of seeking alternative fuels that balance sustainability, energy conservation, efficiency, and environmental protection. The emergence of biofuels, derived from sources like vegetable oil and biodiesel, offers promising solutions. Furthermore, the development of biofuels can stimulate rural economies by creating new income sources and job opportunities. Biodiesel, as a viable alternative for conventional diesel engines, requires minimal modifications for implementation. Its energy density and cetane number are comparable to diesel fuel, resulting in reduced emissions. However, further innovation and technological advancements are crucial to optimize engine performance and ensure cleaner diesel engines. Biodiesel can be used either in pure form or blended with mineral diesel, offering flexibility in application.[4]

When substances harmful to the natural composition of the atmosphere are released, leading to a decline in air quality, it constitutes air pollution, posing significant threats to the planet's well-being. Urbanization and expanding industrial activities are key contributors to this phenomenon, manifesting in various forms such as vehicle exhaust and industrial emissions. Major pollutants stemming from internal combustion engines during fuel combustion include nitrogen oxides (NO), formed by a combination of NO and NO_2, carbon monoxide (CO), unburned hydrocarbons (UBHC), smoke opacity, and residual hydrocarbons.

In order to create biofuels, which are a special sort of liquid fuel that burns cleaner, alcohol is combined with oil from recyclable sources, such as vegetable and animal fats. It is also naturally nontoxic, which makes it even safer. Over the next few decades, a significant amount of petroleum could be replaced globally by biofuels for transportation, including ethanol, biodiesel, and a number of other liquid and gaseous fuels, and a clear trend will begin. The fatty acids found in vegetable and animal fats are converted into alkyl monoesters, which are used to make biodiesel fuel. The characteristics of biodiesel have been demonstrated in numerous experiments to be extremely similar to those of diesel fuel. With little to no modification, biodiesel fuel can be utilized in diesel engines. Because it doesn't include Sulphur or aromatics, biodiesel has a higher cetane number than diesel fuel. A biodiesel must, however, offer a feasible alternative must have a net energy gain, be commercially viable, and be able to be produced in large quantities without reducing the supply of food for human consumption.

Hydrogen is clean and renewable. When hydrogen is used in fuel cells or combustion engines, the only by-product is water vapour, making it a clean energy option. It can be produced from renewable sources like water electrolysis using electricity from solar, wind, or hydro power, further enhancing its sustainability. Hydrogen has a high energy content per unit mass, making it an efficient fuel for transportation and energy storage applications. This high energy density enables longer driving ranges for hydrogen fuel cell vehicles compared to battery electric vehicles. Hydrogen can be used in a variety of applications, including transportation (fuel cell vehicles, hydrogen-powered trains, and ships), stationary power generation (fuel cells for buildings and backup power), and industrial processes (hydrogen as a feedstock for chemical production). When produced from renewable sources, hydrogen can significantly reduce greenhouse gas emissions compared to fossil fuels. It plays a crucial role in decarbonizing sectors such as transportation and industry, contributing to efforts to combat climate change. Fast Refuelling and Scalability: Hydrogen refuelling is fast, similar to gasoline or diesel, which makes it more convenient for users. Additionally, hydrogen infrastructure can be scaled up to meet increasing demand as more vehicles and applications adopt hydrogen as a fuel.

2. Literature Review

The depletion of the environment due to vehicle emissions, the scarcity of crude oil, rising gas prices, and strict laws all require the development of automotive technology. Numerous research projects are being carried out all around the world to meet this urgent requirement. The goal of these initiatives is to investigate alternative fuels as less expensive alternatives to conventional fuels that can improve efficiency and reduce emissions. With these goals in mind, a thorough literature analysis was carried out with an emphasis on the use of biodiesel as a substitute fuel for single injections. Furthermore, the literature includes studies on the operation, emissions, and characteristics of combustion of compression ignition engines that take into account both high pressure and the timing of traditional gasoline injections. Global research is being done on this subject in an effort to identify less expensive substitutes for conventional.

Evaluation of the engine performance, combustion characteristics, and oxidation stability of Prosopis juliflora biodiesel mixed with artificial antioxidants was done.[6] To begin with, four artificial antioxidants were selected in order to evaluate how well they improved oxidation stability: butylated hydroxy toluene, propyl gallate, pyrogallic, and tert-butyl-hydroquinone (TBHQ). As a result, among the previously described synthetic antioxidants, TBHQ performed better and had the longest induction period (10.19 hours) when added to the B20 blend (20% Prosopis juliflora biodiesel and 80% diesel fuel). In the second phase, the B20 sample was treated to different doses of TBHQ (500, 1000, and 1500 ppm) in order to assess the effects of the compound on the engine's performance, combustion, and emission characteristics. Better results were obtained when TBHQ was added to the B20 sample.

The effectiveness, combustion, and emission properties of a fuel blend of diesel fuel, isopropanol (ISP), and Prosopis juliflora biodiesel (PJB) were studied in connection with exhaust gas recirculation (EGR).[7] A diesel engine fitted with a cooled EGR system was used for the testing. Using an ultrasonicate, the PJB and ISP were mixed in an 80:20 ratio. Then, according to volume, four test fuel blends (10%, 20%, 30%, and 40%) were made, magnetically swirled, combined with diesel in equal amounts, and ultrasonicated. Three distinct rates (10%, 20%, and 30%) of EGR were administered, with a consistent injection timing of 230 degrees prior to top dead centre (TDC). The results of the experiment showed that adding a 30% mixture of PJB and ISP.

Biodiesel prepared from a potential and promising alternative feedstock in light of the need for biodiesel from non-edible oil sources and the identification of Prosopis Juliflora (JF) as a highly invasive species in Ethiopia.[8] This study aims to characterize functional groups (using GC-MS, FT-IR, and NMR) and analyse Ethiopian variant Juliflora-based biodiesel (JFB) production through transesterification. It also conducts optimization by investigating the effects of different process parameters and rheological behaviour, which has not been previously reported. The following primary fuel characteristics of Juliflora's methyl ester have been determined by ASTM protocol testing: kinematic viscosity (mm2/s) 3.395, cetane number 52.9, acid number (mg/koh/g) 0.28, density (gm/ml) 0.880, and calorific value (MJ/kg).

In the future, diesel engines will inevitably be a part of our daily lives. Researchers have high expectations for alternative fuel uses on diesel engines due to the high cost of after-treatment technologies required to comply with normative legislation regarding dangerous tail-pipe emissions and the recent increase in fuel prices. This research looks into using hydrogen as a fuel additive in diesel engines. Gas injectors were utilized to provide hydrogen into the intake manifold as a gaseous additive fuel. Additionally, diesel fuel was pumped into the cylinder by the diesel injector and utilized as an igniter. Three different fuel energy contents were selected for the introduced hydrogen: 0%, 25%, and 50% of the total fuel energy.[9]

A comprehensive engine experiment was carried out to assess the performance of a compression ignition engine that was predominantly powered by Jatropha oil and a minor amount of hydrogen.[10] The findings indicated that at maximum power output, 7% of hydrogen mass share increased the brake thermal efficiency. At the optimal efficiency point, there was a noticeable reduction in smoke. Emissions of CO and HC were significantly reduced when the full power output was achieved. Combustion rates increased using hydrogen induction. The experiment's findings shown that even little amounts of hydrogen could greatly improve a vegetable's performance.

Biodiesel is produced from juliflora seeds utilizing a two-stage acid transesterification process followed by an alkali transesterification process, which yields an 80% yield of methyl ester from juliflora oil.[11] Using juliflora biodiesel and its diesel blends, experiments were carried out on a single-cylinder diesel engine. Diesel (D100) and fuel blends (B20, B30, B40, and B100) were examined in the experimental results. The performance and combustion characteristics of B20 were found to be nearly in line with the trend of diesel fuel, according to the results. At full load, the blends B20 and B30 had brake specific fuel consumption (BSFC) of 0.27 kg/KWh, which was closer to diesel's 0.26 kg/KWh. At full load, the Juliflora Biodiesel B100's BTE of 31.11% was more akin to that of diesel (32.05%).

Juliflora oil can be used in CI engine without any engine modification. With Hydrogen induction to biodiesel in CI engine we can increase the BTE and reduce CO and HC emission. Hydrogen induction increases the heat release rate and NO emissions. The viscosity of juliflora oil is more than that of diesel. Hydrogen has a high calorific value. When the concentration of PJB and ISP is increased, it was observed that NO and CO emissions were lowered, while HC emissions increased. Prosopis Juliflora being a new field, research work can be done in this sector. Hydrogen induction can take place at different flow rates in order to analyse the emission and combustion parameters. Many different types of vegetable oils can be explored for the production of biodiesel.

3. Experimentation

The test engine consists of a single-cylinder four-stroke diesel engine connected to an eddy current test bench for supercharging. Equipped with instruments to measure combustion pressure and crank angle. These signals are connected to the computer via the engine display for Pθ-PV diagrams. It is also intended to link air flow, fuel flow, temperature and load sensing. The setup features a self-contained panel box consisting of an airbox, fuel tank, pressure gauge, fuel gauge unit, air and fuel flow meter transmitters, process gauges, and engine gauges. Tachometers are intended for water flow measurements in cooling water and calorimeters.

This setup allows to examine engine performance in terms of braking force, display power, friction force, BMEP, IMEP, brake thermal efficiency, display thermal efficiency, mechanical efficiency, volumetric efficiency, fuel consumption rate, air-fuel ratio, and heat balance. Lab View-based engine performance analysis software package "Engine Software" is provided for online performance evaluation. Computer-assisted diesel injection pressure measurement is available as an option. Engine specifications are shown in table 1, Dynamometer specifications are shown in table 2 and the photographic view of experimental setup is shown in the figure 1.

Table 1. Engine specifications

Parameter	Details
Engine make and Model	Kirloskar TV1
Type	Single Cylinder, four stroke Diesel Engine
Bore Diameter	87.5 mm
Power Rating	5.2 kW at 1500 rpm
Compression Ratio	17.5:1
Stroke Length	110 mm
Speed	1600 rpm max
Cooling system	Water cooled
Dynamometer	Eddy current, water cooled, with loading unit

Table 2. Dynamometer specifications

EDDY CURRENT DYNAMOMETER	
Parameter	**Details**
Make	Techno type
Model	TMEC-10
Max kw	7.5
RPM	1500-1600
Arm Length	185 mm

Figure 1. Photographic view of experimental setup

The exhaust gas composition was investigated with an AVL 437C smoke detector and an AVL DI Gas 444 N gas analyser for the analysis of exhaust gases containing HC, CO, CO_2, and NO. The engine is routinely run under standard test conditions to ensure data consistency and check for errors before performing the required tests. Measurement Range of Gas Analyzer and Smoke Meter is shown in table 3 and table 4.

Table 3. Measurement Range of Gas Analyzer

AVL DI GAS 444 N		
Measurement Data	**Measuring Range**	**Resolution**
CO	0-15% Vol	0.0001% Vol
HC	0-20000 ppm Vol	1ppm/10ppm Vol
CO_2	0-20% Vol	0.1% Vol
O_2	0-55% Vol	0.01% Vol
NO	0-6000 ppm Vol	1 ppm Vol

Table 4. Measurement Range of Smoke Meter

AVL 437C SMOKE METER	
Measurement Data	**Resolution**
Opacity (0-100%)	0.10%
Absorption (K value)	0-99.99m-1 0.01m-1

Prosopis juliflora, a shrub in the Fabaceae family, is well-suited to hot climates and requires minimal water for survival. Also known as mesquite, it is native to the Caribbean and Asia. Its diverse uses include environmental management, wood production, and as forage. The plant's heartwood contains a unique flavanol mosquito repellent, making it an attractive candidate for bio-diesel production. The physical and chemical properties of juliflora seed oil biodiesel, such as specific gravity, viscosity, calorific value, density, flash point, and fire point, have been thoroughly studied and compared with other vegetable oil biodiesels. This research focuses on producing biodiesel from juliflora-seed oil and assessing its performance, combustion, and emission characteristics in diesel engines and diesel blends.

The process of producing biodiesel from Juliflora oil through transesterification involves using methanol (CH_3OH) in the presence of a catalyst (Potassium hydroxide KOH) to break down the raw oil into ester and glycerol molecules. This reaction removes glycerine, a byproduct of biodiesel production, from the oil-alcohol mixture.

The transesterification procedure is outlined as follows: Begin with 1000 ml of Juliflora oil in a container. Weigh out 18 grams of Potassium hydroxide (KOH) as the alkaline catalyst. In a separate beaker, measure 300 ml of methanol. Mix the KOH with the methanol until fully dissolved. Stir the Juliflora oil in a container using a mechanical stirrer while heating it with a heating coil. Maintain a low stirrer speed initially. When the temperature of the Juliflora oil reaches 60°C, add the KOH-alcohol solution to the oil container and seal it tightly. Increase the stirrer speed to 720 rpm and continue stirring for two hours at 60°C, ensuring the temperature does not exceed this to prevent methanol evaporation. The KOH-alcohol solution must be added at 60°C because it generates heat upon mixing, and the oil's temperature needs to be higher to allow proper reactions. After stirring, transfer the oil-KOH-alcohol solution to a glass container for separation. The biodiesel collects in the upper portion, while glycerine settles at the bottom and is removed. Wash the biodiesel with water to remove residual glycerine, repeating until no glycerine remains. Heat the biodiesel to 100°C to vaporize any water content, leaving behind pure biodiesel ready for use. Properties of the fuels and their standard are given in table 5 and 6. Oil is shown in figure 2. The proximate composition and mineral concentration can be investigated using standard analytical methods[18].

Figure 2. Visual image of biodiesel

Table 5. Properties of Fuel

Properties	Diesel	Juliflora oil	Juliflora Biodiesel
Density, kg/m^3 (At 1 atm & 20ºC)	830	930	875
Calorific Value (MJ/Kg)	42000	37600	38000
Viscosity, cst (40ºC)	2.47	37.84	6.808

Table 6. ASTM Standards

Property (for Juliflora Biodiesel B-100)	ASTM
Density at 40 °C(kg/m3)	870-900
Kinematic Viscosity at 40 °C in(mm^2/sec)	1.6-6
Gross Calorific Value (MJ/kg)	>130
Cetane Number	47 min

4. Results and Discussion

The details of the experimental investigation conducted on a single-cylinder mineral diesel engine is discussed. The study involved the use of a combination of Hydrogen and biodiesel blends, operating under single injection mode with varying load rates. The experiment focused on the injection of B100+3LPM(H_2), B100+6LPM(H_2), and B100+9LPM(H_2) biodiesel blends alongside high FIP fuels in internal combustion engines equipped with direct injection fuel systems. The analysis included assessments of emissions such as carbon monoxide (CO), nitrogen oxides (NO), hydrocarbons (HC), smoke opacity, as well as performance metrics like brake thermal efficiency (BTE) and specific fuel consumption (SFC) across each test conducted.

4.1 Performance Analysis

Brake Thermal Efficiency (BTE) serves as a crucial metric in assessing how efficiently a fuel transforms chemical energy into mechanical work. It gauges the efficiency of power generation in relation to the thermal energy produced during fuel combustion. The graph illustrates how factors such as the type of fuel, fuel mixture, fuel injection pressure, and injection duration impact thermal efficiency.[12] Figure 3 displays a comparison of Brake Thermal Efficiency (%) versus Brake Power (kW) across various fuel blends, including 100% Diesel (D100), Juliflora oil Biodiesel (B100), and Biodiesel (B100) with different flowrates of Hydrogen induction (3LPM, 6LPM, 9LPM) under different load conditions.

It is observed that biodiesel with 9LPM flowrate of Hydrogen is having highest brake thermal efficiency with the increase percentage of 17.22% than diesel. The lowest brake thermal efficiency is gained to pure biodiesel (B100) which is decreased by 7.17% than diesel. Other measurements were obtained using Hydrogen at various flow rates and recorded as 6 LPM (7.61%) and 3 LPM (13.26%). Compared to diesel (D100), the addition of Hydrogen has a positive effect on the thermal efficiency of the brakes.

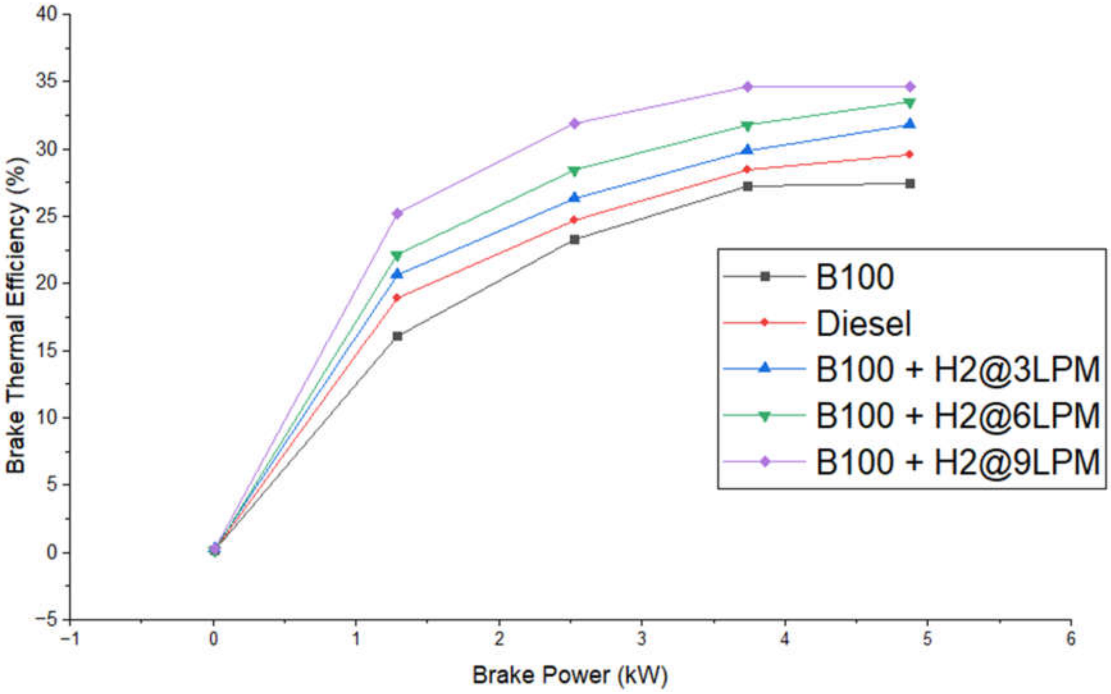

Figure 3. Brake Thermal Efficiency

The study noted that thermal braking efficiency rises with greater loads across various fuel types or blends.[13] With increased load, heat losses decrease gradually, leading to higher fuel consumption and greater heat in the combustion chamber. Hydrogen, known for its high calorific value, favourable combustion conditions, and faster combustion rate compared to diesel, contributes to this effect. There's a trend of increasing Brake Thermal Efficiency (BTE) alongside rising levels of hydrogen injection and braking force (BP).

Specific Fuel Consumption (SFC) is a metric that gauges an engine's fuel efficiency by measuring the amount of fuel consumed per unit of power produced. Figure 4 illustrates a comparison of specific fuel consumption (kg/kWh) against braking power (kW) for various fuel blends, including 100% Diesel (D100), Juliflora oil Biodiesel (B100), and Biodiesel (B100) with different levels of Hydrogen blending (3LPM, 6LPM, 9LPM) across different load conditions.

Pure biodiesel (B100) consumes more fuel compared to diesel and other hydrogen-blended biodiesel fuels at both lower and higher loads. Specifically, B100 consumes 6.25% more fuel than diesel. Conversely, the Biodiesel blend with 9LPM of Hydrogen shows the lowest fuel consumption. It was observed that B100+9LPM consumed 21.87% less fuel than diesel.

The introduction of hydrogen in different blends (B100, B100 + 3LPM(H2), B100 + 6LPM(H2), and B100 + 9LPM(H2)) results in varying SFC values at different flow rates, such as 0.34 kg/kW-h, 0.3 kg/kW-h, 0.28 kg/kW-h, and 0.25 kg/kW-h, respectively, whereas the diesel SFC value is 0.32 kg/kW-h.

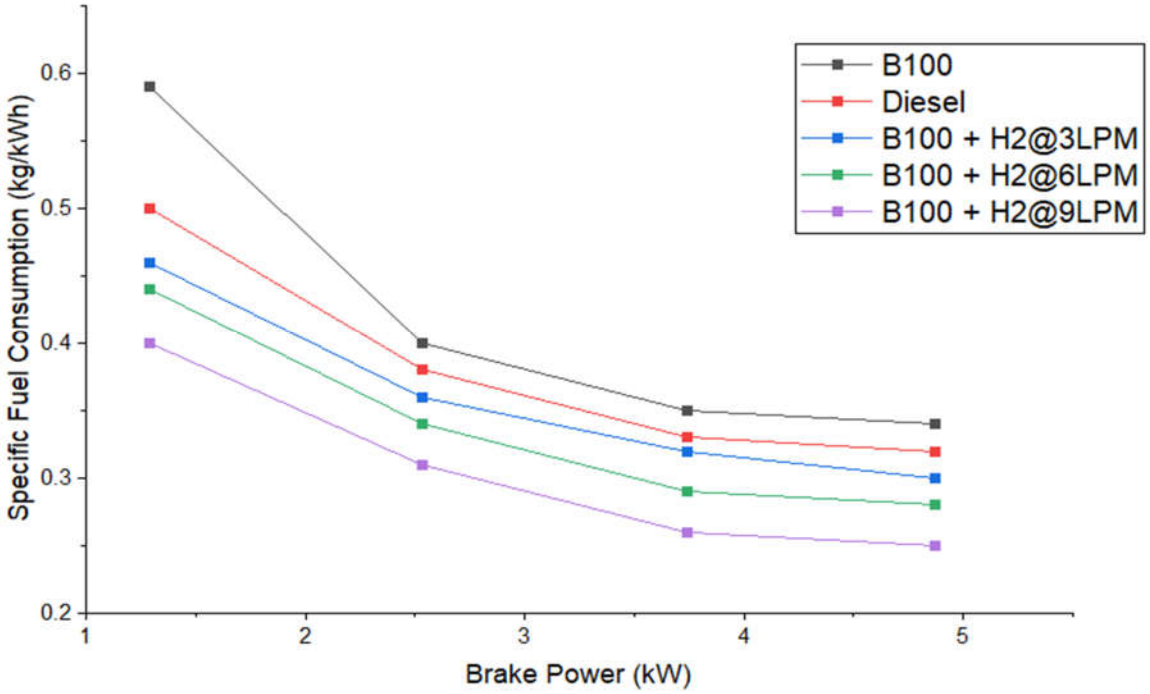

Figure 4. Specific Fuel Consumption

Biodiesel (B100) exhibits a lower density than diesel fuel due to its chemical makeup. This difference can lead to reduced engine efficiency and increased fuel consumption. Additionally, B100's higher viscosity can contribute to elevated friction and wear within the engine, further impacting efficiency and fuel usage, resulting in a higher Specific Fuel Consumption (SFC).

However, the injection of Hydrogen gas leads to a reduction in biodiesel consumption. Increasing Hydrogen induction results in decreased fuel consumption. A lower cetane number can lead to a shorter ignition delay, reducing the time available for air and fuel to mix adequately.[14] This can result in a weaker mixture during the premixed combustion phase, ultimately contributing to a relatively lower SFC.

4.2 Emissions Analysis

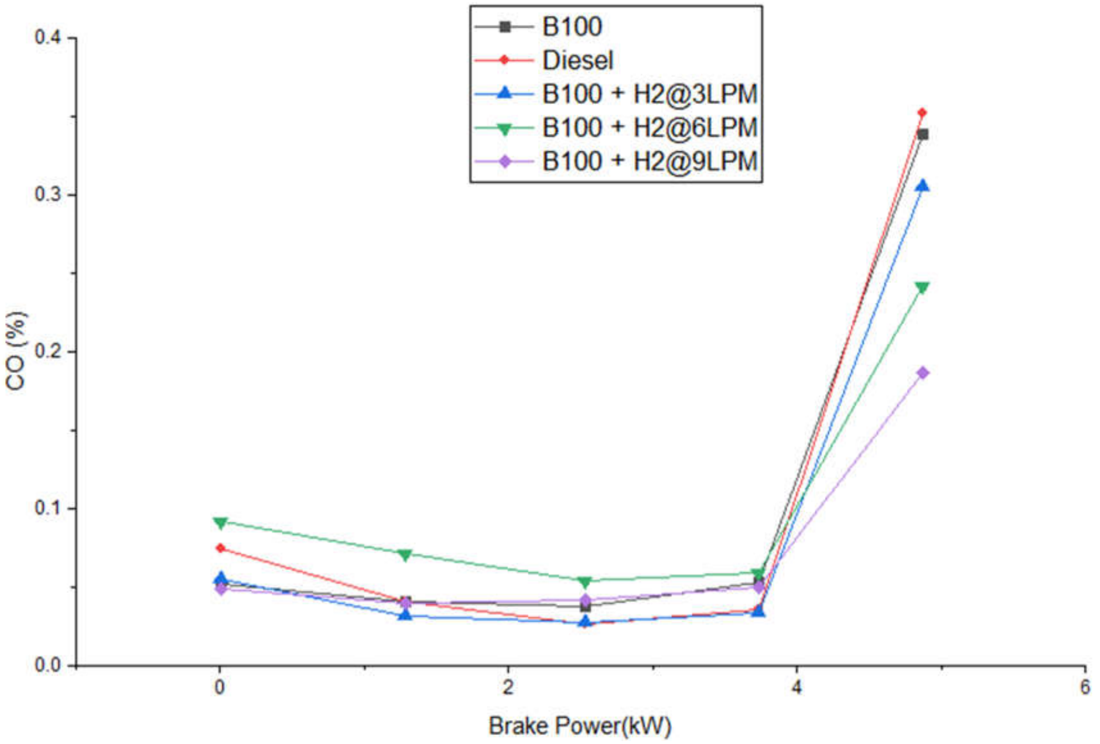

Figure 5. Carbon monoxide Emission

Incomplete combustion within the combustor is the primary cause of CO production, a by-product of combustion resulting from local oxygen deficiency. CO oxidation is significantly affected by combustion temperature and the availability of additional air. Figure 5 illustrates the variation of carbon monoxide emissions for different fuel blends, including 100% Diesel (D100), Juliflora oil Biodiesel (B100), and Biodiesel (B100) with varying levels of Hydrogen blending (3LPM, 6LPM, 9LPM) under different load conditions.

B100 biodiesel emits lower CO emissions compared to diesel because of the oxygen content in biodiesel, leading to more complete combustion cycles and leaner mixtures than diesel. However, a blend of Hydrogen and biodiesel generates more CO than diesel due to oxygen deficiency during ignition, insufficient oxygen levels, and the carbon content in the fuel not adequately contributing to the ignition process, resulting in CO emissions from the engine exhaust. CO emissions from Hydrogen occur under partial load due to reduced cylinder temperatures during the expansion stroke and incomplete burning of Hydrogen. The gradual addition of 3 LPM of Hydrogen leads to a progressive decrease in CO emissions.

A deadly gas, carbon monoxide is not only an emission, but also a fuel whose chemical energy is not properly utilized. Diesel engines are typically run with excess air and therefore have very low CO emissions[15]. In the case of multiple injections, some of the injected pilot fuel ends up in very lean zones, too low temperature zones, or combustion regions.

Here, a proper pilot fuel-air mixture results in a leaner mixture that burns at a higher heat release rate and produces lower CO emissions. Alternatively, an improved pilot fuel-air mixture results in an overly lean charge where no combustion occurs, leading to lower volumes. Increased heat release rate and CO production for pilot injection. Overall, all mixes showed a significant reduction compared to B100+ 3LPM, with B100+ 6LPM, B100+ 9LPM, B100 and D100 showing 13.35%, 31.25%, 46.87% and 3.69% respectively.

HC emissions are primarily formed when fuel molecules are not completely burned during the combustion process[16]. This can occur when the air/fuel mixture is too rich and impurities in the Figure 6 depicts the comparison between HC emissions (%) vs Brake Power (KW) for different blend of fuels like 100% Diesel (D100), Juliflora oil Biodiesel (B100), Biodiesel (B100) with different blends of Hydrogen (3LPM, 6LPM, 9LPM) at various loads.

B100 with Hydrogen has lower HC emissions of 43 ppm compared to various fuels and diesel without Hydrogen. At full load, diesel fuel emits more hydrocarbons (HC) at a rate of 59 ppm. This is 30% more than B100 + 1L (H2) blended fuel. Hydrocarbon emissions were measured at 43, 57, 47 ppm at B100, B100 + 1 L (H2) and B100 + 2 L (H2), respectively. These graphs show how increasing the percentage of oxygenated fuel in diesel fuel reduces HC emissions. These decreases indicate that the fuel is gradually being completely burned and HC levels are dropping dramatically.

Complete combustion of gaseous fuel has been shown to steadily reduce HC emissions for all loads by adding Hydrogen at a rate of 3 LPM. The graph shows that 9 LPM blends of B100 biodiesel and Hydrogen provide the highest HC emission reductions. Reduced HC emissions come from faster burn rates and improved combustion efficiency. When Hydrogen and biodiesel are mixed at high concentrations, there is insufficient oxygen for the carbon to react, resulting in incomplete combustion and increased HC emission.

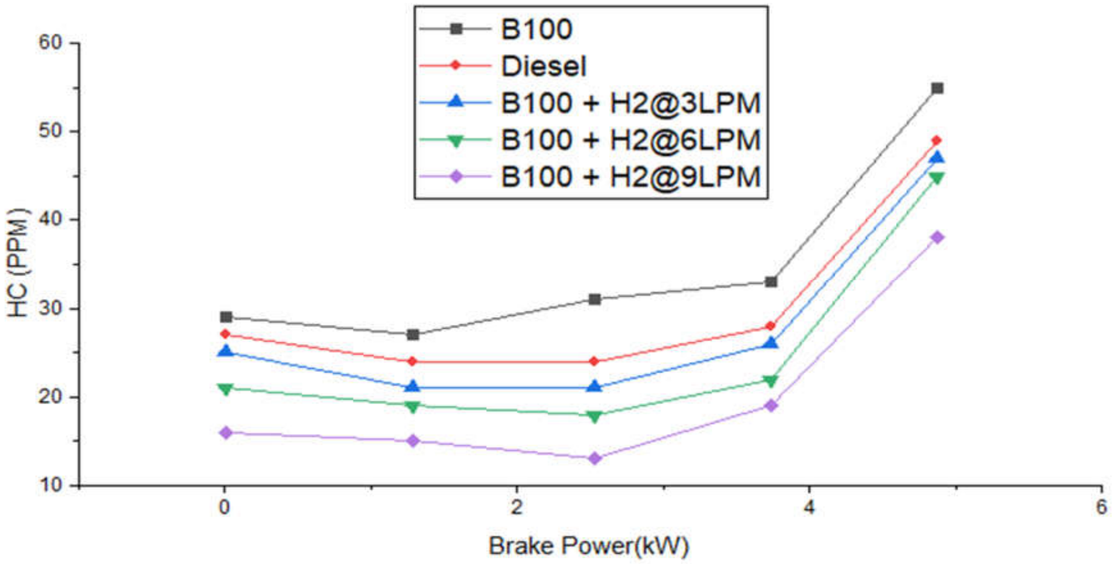

Figure 6. Hydrocarbon Emission

Nitrogen oxides (NO) form when nitrogen and oxygen combine at elevated temperatures[17]. In engines, fine fuel particles initiate combustion at the air-fuel interface, leading to NO production when local temperatures near the fuel spray surpass certain thresholds. NO generation primarily stems from two factors: high temperatures and oxygen availability. Compression ignition (CI) engines often operate with high compression ratios and lean mixtures, elevating temperatures and fostering NO emissions.

The elevated molecular oxygen content in biodiesel, coupled with high combustion temperatures, contributes to increased NO levels in engine exhaust. Figure 7 illustrates that using biodiesel (B100) tends to raise overall NO emissions. However, the trend indicates a decrease in NO emissions with increasing Hydrogen injection. This decreases results from the combustion environment created by burning Hydrogen and air at lower temperatures.

NO formation results from two factors: combustion chamber temperature and oxygen concentration when using biodiesel. At lower loads, Biodiesel (B100) exhibits the highest NO emissions, followed by Diesel, B100+1LPM, B100+2LPM, and B100+3LPM. Conversely, at higher loads, Biodiesel (B100) still has the highest NO emissions, followed by Diesel, B100+1LPM, B100+3LPM, and B100+2LPM. This graph demonstrates a consistent pattern of NO emissions across all loads, with our tested WCO blends showing the lowest emissions. This reinforces the suitability of our tested blends, as they emit significantly less NO compared to Diesel.

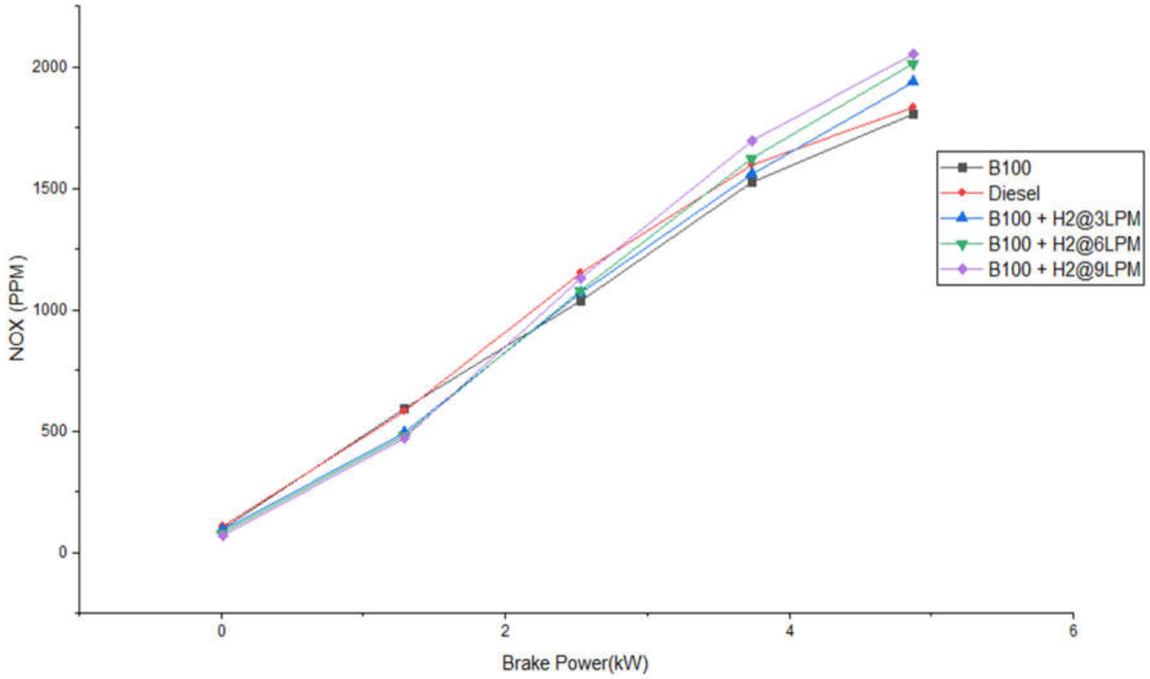

Figure 7. Nitrogen Oxide Emissions

NO generation is influenced by combustion chamber temperature and oxygen concentration when using biodiesel. Due to spray characteristics, oxygen content, and adiabatic flame temperature, combustion chamber gas temperatures are higher, leading to increased NO emissions.

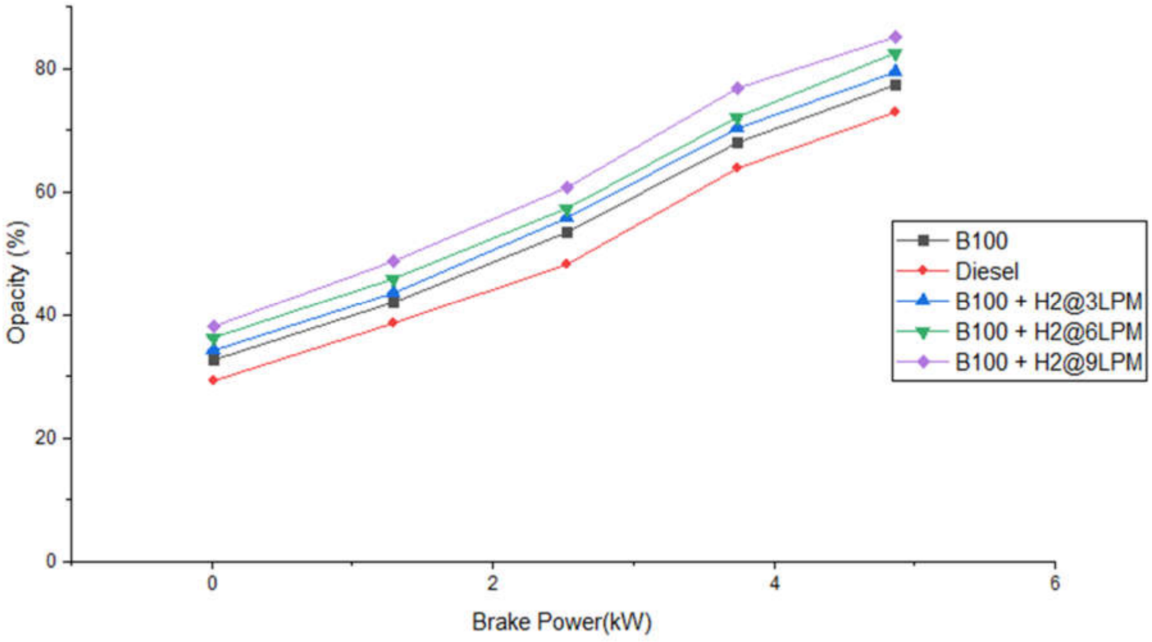

Figure 8. Smoke Opacity

Smoke formation primarily stems from incomplete fuel combustion, although factors like air/fuel ratio, fuel distribution within the mixture, and fuel composition also influence it significantly. Recent experimental findings indicate that biodiesel blends in diesel engines typically produce lower smoke opacity compared to pure diesel across various operating conditions.

Figure 8 shows the variation of smoke opacity for different fuel blends, including 100% Diesel (D100), Juliflora oil Biodiesel (B100), and Biodiesel (B100) with varying levels of Hydrogen blending (3LPM, 6LPM, 9LPM) at different loads.

A B100+3LPM biodiesel blend at full load demonstrates a 6% increase in smoke opacity. This increase is attributed to the higher oxygen concentration and lower carbon content present in biodiesel. The oxygen molecules in biodiesel contribute to more uniform and complete combustion, oxygenating fuel-rich zones and minimizing localized areas of excess fuel, thereby preventing primary smoke formation.

The lack of aromatics in biofuels is an added benefit of less smoke. The smoke opacity levels reduces for B100+9LPM, B100+6LPM, and biodiesel compared to running on clean diesel.

Smoke density was reduced by using a lower blend. This was caused by the development of proper air-fuel ratios using air-fuel mixtures. Biodiesel chemical composition and oxygen content were other important factors.

4.3 Combustion Parameters

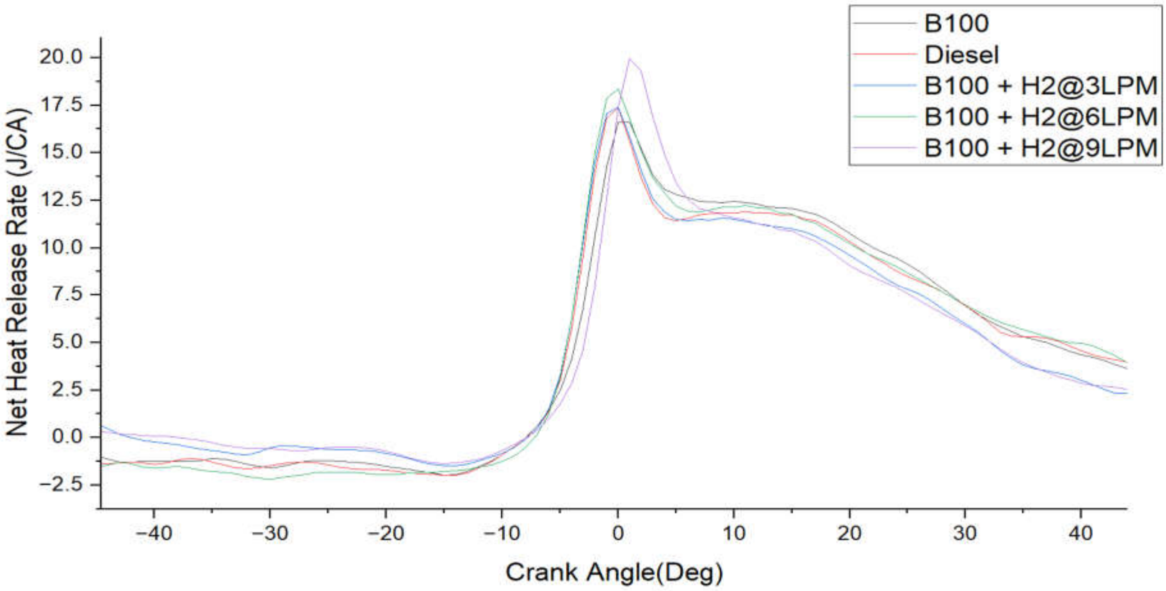

Figure 9. Net Heat Release Rate

The Net Heat Release Rate (NHRR) analysis is utilized to examine the combustion processes within the cylinder, considering both the physical and chemical properties of the fuel being tested, which influence the rate of heat release. Across all tested fuels, a negative heat release is observed after fuel injection and before reaching top dead centre. This negative release is due to the cooling effect within the cylinder caused by fuel vaporization during the ignition delay period. Following the start of combustion (SOC), the Net Heat Release Rate (NHRR) becomes positive.

Control of the NHRR by the mixture ratio results in rapid combustion of the premixture after ignition retard, followed by a more diffuse burn. Figure 9 illustrates the trends in net heat release for both diesel and biodiesel blends, highlighting these characteristics in the combustion process.

The B100+9LPM blend exhibits a peak NHRR value of approximately 19.94 J/°kw, occurring earlier compared to other fuel conditions. This earlier peak is attributed to the more efficient combustion of oxygen in the fuel, combined with the higher calorific value and ignition limit of Hydrogen over biodiesel.

The burn velocity diagram illustrates four distinct phases: the ignition delay phase, the premixed combustion phase, the mixture-controlled combustion phase, and the late combustion phase. Analysis of heat release rates during Hydrogen injection indicates a clear progression of detonation, followed by premixed combustion, a slight decline in combustion rate during the second stage of gas combustion, and a subsequent sharp increase during the third stage, primarily driven by diffusion combustion.

Higher intake air Hydrogen content leads to a direct increase in the heat release rate during the premixed phase. The research indicates that only the diesel fuel injected by the injector burns under controlled conditions, while the Hydrogen in the intake air decomposes during the mixture-controlled combustion phase. This decomposition of Hydrogen has been observed to boost the heat release rate during the premixing stage of combustion, particularly evident in B100+9LPM operation, consequently elevating the in-cylinder pressure.

Figure 10 displays the cylinder pressure changes and locations of peak pressure associated with various biodiesel blends, different Start of Injection (SOI) timings, and crank angle (CAD). The combustion efficiency of gasoline relies on the cylinder load, which indicates how well gasoline mixes with air and burns. Additionally, we explore how cylinder pressure increases with higher loads for all fuels at a given speed and injection time. This increase occurs because optimal loading allows for more fuel introduction and enhanced combustion, resulting in improved power output.

Across different fuels, there is minimal variation in cylinder pressure or altitude, indicating that gasoline's thermal performance translates effectively into mechanical performance. The variation of cylinder pressure is shown for various fuel blends, including 100% Diesel (D100), Juliflora oil Biodiesel (B100), and Biodiesel (B100) with varying levels of Hydrogen blending (3LPM, 6LPM, 9LPM) at different loads.

B100+9LPM biodiesel blend has the highest peak pressure compared to diesel fuel and other blends of biodiesel. This is likely due to the higher cetane index of biodiesel blended with Hydrogen, which results in better combustion due to the higher amount of oxygen in the fuel, thus burning more fuel during the diffusion stage of combustion. The peak pressure of the B100+9LPM mixture is approximately 48.12 bar at 30°C.

Peak pressure is further increased due to increased ignition delay and combustion velocity in dual fuel operation with exhaust gas recirculation using Hydrogen induction at maximum load. This is because the combustion rate is high and ignition is delayed. The rapid combustion of Hydrogen, in contrast to diesel fuel, may be responsible for the increased peak combustion pressure of Hydrogen.

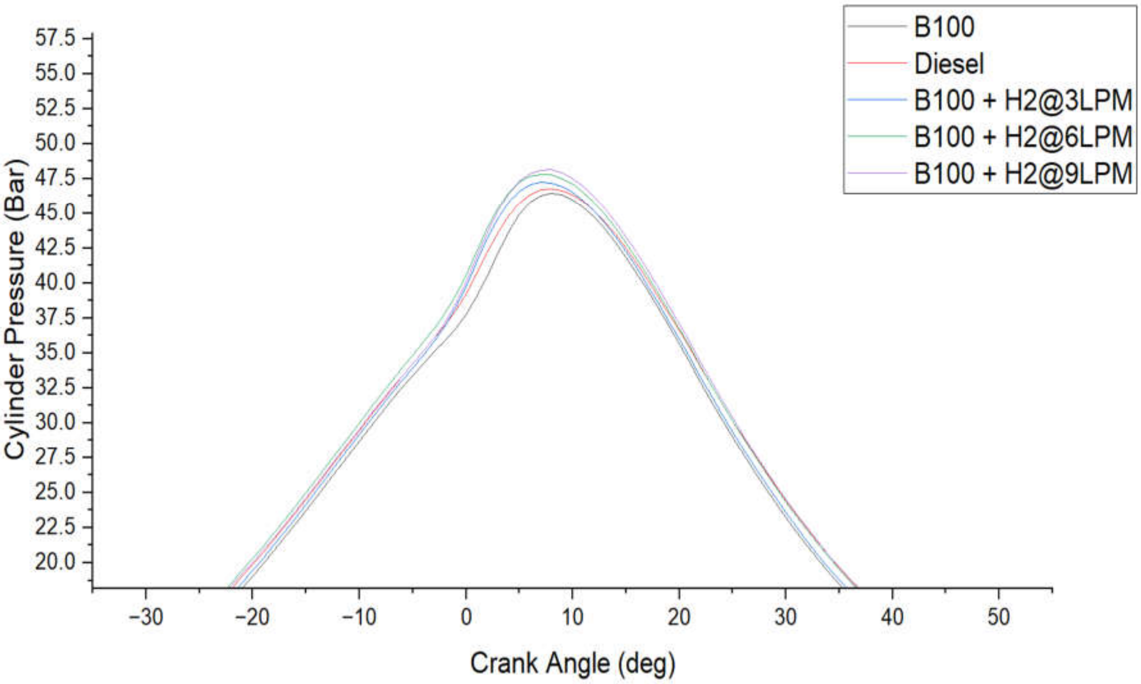

Figure 10. In cylinder pressure

5. Conclusion

This study experimentally investigated the effect of introducing hydrogen gas into the intake air on engine performance and emissions using a naturally aspirated, pre-chamber, single-cylinder, water-cooled diesel engine. Below is a summary of the tests performed at 1500 rpm with various loads.

1. The Brake Thermal Efficiency (BTE) of B100+H2@9lpm is 17.21% more than that of Diesel and 26.27% more than that of B100.

2. The Specific Fuel Consumption (SFC) of B100+H2@9lpm is 21.87% less than that of Diesel and 26.47% less than that of B100.
3. An increment of 13.69% was observed in NO emission of B100+H2@9lpm compared to Biodiesel B100. The NO emission of B100+H2@9lpm is 11.83%more than that of diesel.
4. A decrement of 44.83% was observed in CO emissions of B100+H2@9lpm compared to Biodiesel B100. The CO emission of B100+H2@9lpm is 46.87% less than that of diesel.
5. A decrement of 30.9% was observed in HC emissions of B100+H2@9lpm compared to Biodiesel B100. The HC emission of B100+H2@9lpm is 22.44% less than that of diesel.
6. An increment of 10.36% was observed in Opacity of B100+H2@9lpm compared to Biodiesel B100. The Opacity of B100+H2@9lpm is 17.03% more than that of diesel.
7. An increment of 3.65% was observed in Cylinder Pressure of B100+H2@9lpm compared to Biodiesel B100. The Cylinder Pressure of B100+H2@9lpm is 2.88% more than that of diesel.
8. An increment of 20.12% was observed in Heat Releases Rate of B100+H2@9lpm compared to Biodiesel B100. The Heat Releases Rate6 of B100+H2@9lpm is 14.86% more than that of diesel.

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Author contributions

The authors confirm to have contributed to the preparation of the manuscript as follows: Conceptualization and Design, Methodology and Writing: Dr.V.Rajasekar; Resources and Data Curation: Akash Todi, Soham Patra; Review and Editing: Dr.G.Balaji.

Appendices/Supplemental material

None.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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