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IMPROVING EFFICIENCY AND EMISSION CHARACTERISTICS OF A DI DIESEL ENGINE USING HYDROGEN-ENRICHED JULIFLORA BIODIESEL-DEE BLENDS

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ABSTRACT

Investigations were carried on single cylinder, four stroke constant engine speed for varying load conditions direct injection engine fuelled by Juliflora biodiesel along with hydrogen t and Diethyl Ether as an additive at 5% by volume. Hydrogen was sent through intake manifold in varying proportions as 4 lpm, 6 lpm and 8 lpm. Brake thermal Efficiency and Specific fuel consumption as performance and CO, UHC, CO₂, NO_x and Smoke Opacity as emission characteristics of the engine were observed. While enriching the hydrogen along the JFB20DEE5 varying flow rates such as 4 lpm, 6 lpm and 8 lpm the BTE is increased to 2%, 5.1% and 10 % than the diesel. As the load increases the brake thermal efficiency also increases for biodiesel blends of JFB20 but when hydrogen is added with the blends it is observed that the brake thermal efficiency has been increased by 10% for JFB20DEEH8 than diesel at higher load. Compared to diesel, the percentage of the SFC decreases for increasing the loads for the all the JFB20 blends. Compared to diesel the JFB20 blend give more fuel consumption than diesel and also it continues in the case of the blend when DEE is added. It is noticed that when the JFB20DEE5 is enriched by hydrogen with varying flow rates the BSFC is decreased. It is observed that at full load the BSFC decrease by 4% for the JFB20DEE5H8 blend than pure diesel. When the blend is enriched by hydrogen for the 4 lpm, 6 lpm and 8 lpm, the CO emission is considerably decreased for the half load and full load conditions as 9%, 13% and 17% respectively. The UBHC emissions are decreases when the Diethyl Ether is added to blend it gives 9% HC reduction as the load increases. For the blends JFB20DEE5H4, JFB20DEE5H6 and JFB20DEE5H8, UBHC is decreasing by 9% to 28% at full load than diesel. NO_x emissions are high for pure diesel. Increasing load gradually increases the NO_x emission for all tested fuels. At the highest hydrogen flow rate 8 lpm (JFB20DEE5H8) the cylinder pressure is notably higher, reflecting more efficient and potentially more powerful combustion. The data specifically highlights that at 100% load, 8 LPM hydrogen flow produces an approximate 10.3% increase in cylinder pressure compared to using diesel fuel. At 100% load, the HRR for JF B20 reaches 32.22 J/°CA, and when adding 5%DEE it increases to 35.9J/°CA. For 8 LPM hydrogen is introduced, this value goes up to 41.74 J/°CA-an increase of 3.41 J/oCA or an enhancement by 9%.The high flame speed and energy density of hydrogen improve overall combustion efficiency, resulting in higher heat release and pressure.



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I. INTRODUCTION

Internal combustion engines and traditional fossil fuels play a major role in today's electricity and transportation networks. Diesel engines in particular continue to be widely used in power generation because of their unavoidable benefits, which include high power to weight ratios and efficiency levels. Studies on lowering pollutants released by diesel engines are another important issue that needs to be fully addressed by scientists because undesirable exhaust emissions like smoke, unburned hydrocarbons, CO, particulate matter, and NO_x emitted from engines have detrimental effects on both the health of living things and the environmental climate [1]. Researchers are being compelled to look at emission reduction technology and discover cleaner, renewable, and more environmentally friendly fuel alternatives without changing the engine [2]. Alternative energy sources like biofuels have a great deal of potential to displace fossil fuels. They provide a number of benefits, including regional growth, sustainability, renewable energy, and a decrease in greenhouse gas emissions [3]. Bora and Saha [4] examined the performance and emission characteristics of a single cylinder, DI, water-cooled CI engine using rice bran biodiesel and raw biogas at three different compression ratio changes.

The highest brake thermal efficiency of 18 was recorded at fixed IT 23 bTDC, accompanied by a 17.6% and 17.2% drop in CO and UHC emissions, respectively. Using edible oils to extract biodiesel could lead to a problem with independence in vegetable farming. The extraction of biodiesel from non-edible vegetable oils is the only remaining solution for reducing the usage of vegetable oils. Due to the enormous demand for edible oils, the use of non-edible oils in comparison to edible oils is remarkable in developing countries [5]. It is therefore preferable to utilize both edible and non-edible oil, depending on what is available. This will lessen reliance on a single fuel and address seasonal fluctuations. Some inedible oils, such as those from *Jatropha curcas*, *Calophyllum inophyllum*, *Pongamia pinnata*, *Croton megalocarpus*, and *Madhuca indica*, have been explored as alternative fuels in recent years [6]. Abedin et al. [7] have investigated the qualities of biodiesel made from non-edible oil. They concluded that biodiesel was the best fuel to replace diesel because its attributes were nearly identical to those of diesel. The use of hydrogen in CI engines has been viewed as a good substitute in recent years because of its benefits, which include its high calorific value, lack of carbon structure, and non-toxicity [8].

Furthermore, hydrogen can be quickly ignited, consumed cleanly, and reused; yet, its main advantages are limited to greater nitrogen oxides, explosions, and dangerous activities [9]. In order to assess the performance and emission characteristics, Kumar et al. [10] demonstrated the induction of hydrogen at varying flow rates alongside diesel in a four-stroke, single-cylinder CI engine. They claimed that compared to diesel fuel, the fuel consumption was reduced and the thermal efficiency was raised by up to 10.7%. CO and HC emissions were reduced by 16% and 7%, respectively. The impact of adding hydrogen to an IC engine was examined by Saravanan et al. [11], who also assessed the exhaust gases and thermal efficiency. The results showed that other exhaust gases, such as UHC, CO, and carbon oxides, was reduced while the BTE increased by up to 17%. Karagoz et al. [12] carried out an experiment to determine how 30% hydrogen enrichment affected CI engines at various loads. The authors found that emissions such as smoke, CO, and CO₂ were significantly reduced by 68%, 29.5%, and 51.3%, respectively, and that the BTE was reduced by 8.5%. In an experiment conducted by Kumar et al. [13], pilot fuels for the CI engine were diesel and *Jatropha* oil after a minor quantity of hydrogen enrichment.

With the exception of a 16% increase in nitrogen oxide, the results showed that BTE increased by 8.15% and that HC, CO, and smoke opacity emissions decreased by 30%, 41.2%, and 40.5%, respectively. When using *Jatropha Curcas* and hydrogen in dual fuel mode, the efficiency was nearly identical to that of diesel fuel at maximum load. Serin and Yildizhan [14] looked at the performance and emissions of tea seed oil biodiesel blends in a diesel engine with hydrogen present. The performance of a single-cylinder, four-stroke, DI diesel engine powered by rapeseed oil, rapeseed oil methyl ester, and diesel as pilot fuel by introducing hydrogen was examined by Geo et al. [15]. There were minimal exhaust gas emissions and enhanced BTE and BSFC by 5.5% and 12.3%, respectively. The primary benefits of bio fuel include its high biodegradability, low pollution emissions, renewability, and flash point. The conventional oil seed crops used to make biodiesel include mustard, rape seed, ground nut, safflower, sunflower, linseed, palm, soybean, and many more. Should edible oils be utilized to produce biodiesel, the globe will experience a severe food scarcity. Therefore, biodiesel is being produced using non-edible oil sources. This can aid in reducing the amount of non-edible seeds used to produce biodiesel.

The production of biodiesel from a variety of edible and non-edible vegetable oils, such as cottonseed oil, olive oil, wild jojoba oil, mustard oil, soybean oil, waste cooking oil, and wild jojoba oil, has gained a lot of attention in the literature. However, there is a dearth of comprehensive information regarding the production of biodiesel from *Juliflora* oil and its engine studies. One of the problematic and invasive alien species in the Afar and Somali regions was the evergreen tree *Prosopis Juliflora* (PJ), which later expanded to Ethiopia's Southern States and Nationalities Regional Administration in the Great Rift Valley, which is headed towards South Omo [16]. A tree may produce seeds that weigh between 5 and 10 kg, depending on the climate and surroundings. It is projected that PJ will produce 2230 kg/ha of pods at a density of roughly 20 kg/tree. Due to its non-food-related status, it is not as vulnerable to dietary safety concerns as other food crops. As an example, bio-oils were previously produced from maize, wheat, and sorghum [17]. In order to solve this issue, transesterification is a widely used technique to lower the viscosity of vegetable oil [18], which is believed to be the most workable and efficient strategy. The properties of test fuels are given in the table 1.

Table 1: Properties of bio diesel produced from vegetable oils.

S. No.	Properties	Neat Diesel ND	JFB20	DEE	JFB20 DEE5	JFB20 DEE10	JFB20 DEE15
1	Density (kg/m ³)	833	850	715	847	837	831
2	Viscosity (mm ² /s)	2.8	3.2	0.23	3.07	2.93	2.7
3	Calorific Value (kJ/kg)	42500	41520	33.89	41090	42600	42100
4	Fire Point °C	54	65	-			
5	Cetane Index	50	52	125	53	57	61
6	Flash Point °C	50	54	-45	79	73	67
7	Cloud Point °C	-13	-	-	-	-	-

Source: Authors, (2026).

II. EXPERIMENTAL METHOD

II.1 JULIFLORA SEED BIODIESEL PREPARATION

The methods used to make biodiesel from Juliflora seeds, the setup of the hydrogen fumigation equipment, the setup for engine testing, and the analytical techniques used for performance and emission evaluation are all described in this part. The evergreen Juliflora tree, which is native to South America, Central America, and the Caribbean, is usually referred to as mesquite in the United States. This species has gained recognition for its quick development, ability to fix nitrogen, and ability to withstand saline soils and dry conditions. As a result, it has emerged as a resource in difficult ecosystems. Construction materials, charcoal, soil conservation, and the restoration of saline or degraded soils are just a few of the many products and services that Juliflora may offer in ideal circumstances. Juliflora provides a broad range of products, including charcoal, building supplies, firewood, soil conservation, and the restoration of saline or damaged soils, regardless of the weather. Using a small, sharp knife, the pods are sliced lengthwise and crosswise to harvest the seeds of Juliflora, which are then used for cultivation and oil extraction.

II.1.1 Feedstock collection and preparation

The shrub *Prosopis Juliflora* as Shown in Figure 1 (a) belongs to the Fabaceae family. It is regarded as a primitive plant that thrives in hot climates with little water needed for sustenance. This type of mesquite is indigenous to Asia and the Caribbean. Its applications include fodder and wood for environmental management. The plant contains an aberrant flavone mosquito in its heartwood. These are more compelling arguments in favor of developing bio-diesel facilities. Key physical and chemical characteristics of the bio-diesel made from Juliflora seed oil are investigated, including density, specific gravity, viscosity, calorific value, flash point, and fire point. They work well with the majority of other vegetable oil biodiesel. Therefore, the experimental work focuses on producing biodiesel from Juliflora seed oil and examining the performance, combustion, and emission characteristics of diesel engines that use biodiesel made from soy and its diesel mixes. The fruiting Juliflora seeds, seed oil and extraction method are shown in figure 1(a), 1(b) and 1(c) respectively. It is projected that PJ will produce 2230 kg/ha of pods at a density of roughly 20 kg/tree. Due to its non-food-related status, it is not as vulnerable to dietary safety concerns as other food crops. As an example, bio-oils were previously produced from maize, wheat, and sorghum. In order to solve this issue, transesterification is a widely used technique to lower the viscosity of vegetable oil, which is believed to be the most workable and efficient strategy.

II.1.2 Juliflora seed oil extraction

Oil extraction from *Prosopis Juliflora* is typically performed using either pyrolysis of the biomass or mechanical/solvent extraction of seeds, depending on the intended application. In the pyrolysis method, the lignocellulose biomass of Juliflora—such as stems, branches, and leaves—is thermally decomposed in the absence of oxygen at temperatures between 350°C and 550°C. This process breaks down complex organic polymers like cellulose, hemicellulose, and lignin into simpler volatile compounds. These vapors are then cooled in a condenser to obtain a dark, viscous liquid known as bio-oil. The remaining products include syngas, which can be recycled for heating, and biochar, which can be used as a soil enhancer or fuel. Pyrolysis is widely used because it converts low-value biomass into high-value liquid fuel, making Juliflora a viable resource for renewable energy generation. In contrast, seed oil extraction focuses on obtaining oil directly from Juliflora seeds.

The seeds are first cleaned, dried, and mechanically crushed to increase surface area. Mechanical pressing using an oil expeller can extract a small amount of crude oil, though the yield is generally low. To improve recovery, solvent extraction using a hydrocarbon solvent like hexane is often employed. The solvent dissolves the oil from the crushed seed powder, forming a solution that is later heated to evaporate and recover the solvent, leaving behind crude seed oil. This oil undergoes filtration and refining to remove impurities, resulting in a usable product. Both methods highlight the versatility of Juliflora as a bio-resource. While pyrolysis provides a sustainable route for producing bio-fuels, seed-based extraction offers potential for small-scale applications such as soap making and biodiesel production. The choice of method depends on required yield, application, and available equipment. The Juliflora seed oil extraction workflow is illustrated in the Figure 2.



Figure 1: Juliflora Seeds.
Source: Authors, (2026).



Figure 2: Juliflora Seeds oil.
Source: Authors, (2026).

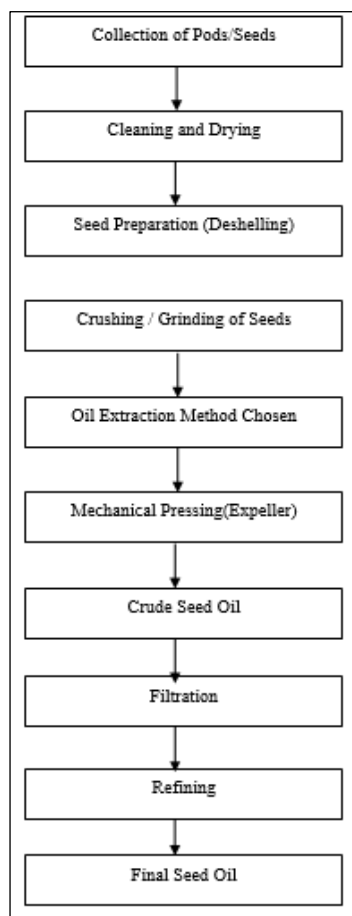


Figure 3: Juliflora oil extraction workflow.
Source: Authors, (2026).

II.1.3 Transesterification (Alcoholysis)

Transesterification is a chemical process that creates esters and glycerol by reacting edible and non-edible oil with alcohol. To increase the yield and rate of a reaction, catalysts can be employed. The transesterification process typically uses alcohols such propanol, butanol, methyl alcohol, ethyl alcohol, and alcohol. The most common alcohols utilized in this chemical reaction are typically methyl and ethyl. It is inexpensive, has good physical and chemical qualities, reacts with triglycerides quickly, and is more soluble in oil.

II.2 ENGINE SETUP AND EXPERIMENTATION

A four-stroke, single-cylinder, water-cooled, constant compression ignition engine is used for all experimental testing. An eddy current dynamometer is connected to the engine arrangement. The testing blends' performance, combustion, and emission properties are evaluated using the eddy current dynamometer as a loading mechanism. An electric knob allows the user to adjust the load on an eddy current dynamometer. A supply tank with a valve makes up the fuel supply system. A burette tube, which is attached to the valve, is used to measure the amount of fuel used per unit of time. The number of thermocouples and sensors that are connected to the engine is used to measure the temperatures at the key locations. At the air intake, air (exhaust gas) outlet, hot water outlet, and cooling water inlet, the temperatures are recorded. Figure 2 displays the schematic diagram of the test engine used in this investigation.

The water supply supplied by the water jackets cools the engine. Table 2 provides the test engine's numerous technical specifications. The data acquisition system (DAQ) that comes with the engine is used to tabulate the various data needed to determine the engine's performance and combustion parameters. EGT, CO, NO_x, UBHC, and smoke opacity data are measured by the emission analyzer attached to the exhaust pipe. Table 3 lists all of the instrument specs used in these investigations. In the initial setup, the engine is tested using only diesel to operate for 20 to 30 minutes, and readings are taken under various load scenarios. The DAQ's combustion parameters, performance statistics, and exhaust emission analyzer readings were compared to those of the DEE and biodiesel blends. The prepared blend B20 is put back into the fuel tank after a series of readings from pure diesel are finished. Also, furthermore tests were done at constant engine speed at 1500rpm for varying load conditions such as 0, 25, and 50, 75 and full loads. Hydrogen was sent through intake manifold in varying proportions such as 4 lpm, 6 lpm and 8 lpm with JFB20DEE5. To ensure that the engine exclusively uses the B20 biodiesel blends such as it is then left to run for the first six to eight minutes. Performance and emission data for various loading scenarios were recorded a short while later. For each of the other prepared blends, the same steps were repeated. The combination of test fuel and additives matrix is depicted in the table 3.

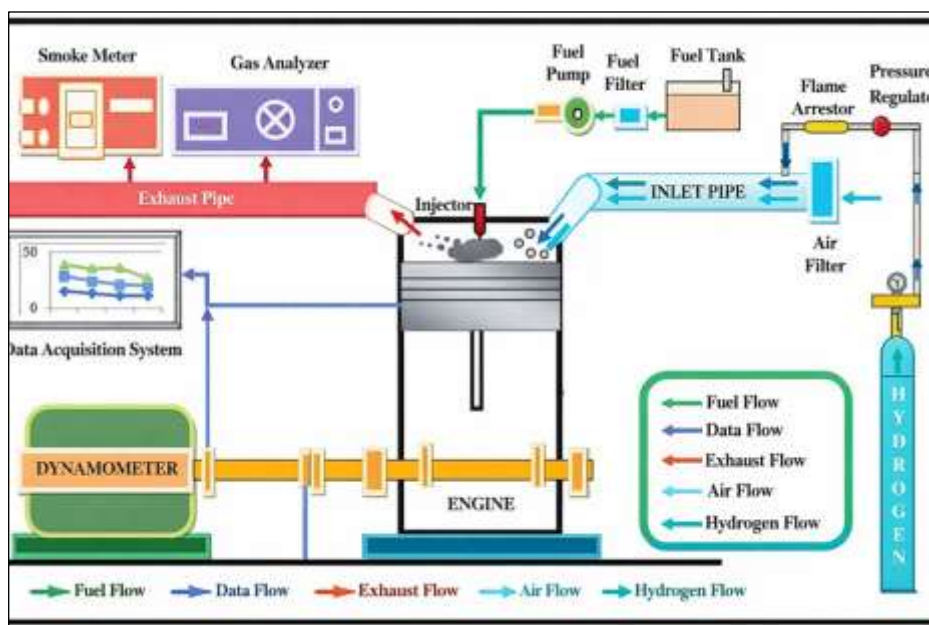


Figure 4: Tested engine setup with DAQ

Source: Authors, (2026).

Table 2: Specifications of test engine.

S. No.	Particulars	Details
1	Engine (make)	Kirloskar
2	Type	Vertical, Water Cooled
3	Stroke	Four
4	Number of cylinder	One
5	Bore (mm)	80
6	Stroke (mm)	110
7	Compression Ratio	17.5:1
8	Maximum Power (kW)	5
9	Speed (rpm)	1500
10	Dynamometer type	Eddy Current
11	Injection Timing	23° Before TDC
12	Injection Pressure (kgf/cm ²)	200, Direct Injection

Source: Authors, (2026).

Table 3: Test matrix

Fuel	Blend rate	Load and Speed
Diesel	100% pure diesel (1000 ml)	Loads range: 0, 25, 50, 75 & 100% Speed: 1500 rpm
JFB20	Diesel (800 ml)+Juiliflora seed oil Biodiesel (200 ml)	
JFB20+DEE5	Diesel (800 ml)+Juiliflora seed oil Biodiesel (200 ml)+DEE5,	
JFB20+DEE5+H2 4 lpm	Diesel (800 ml)+Juiliflora seed oil Biodiesel (200 ml)+DEE5+Hydrogen 4 lpm	
JFB20+DEE5+H2 6 lpm	Diesel (800 ml)+Juiliflora seed oil Biodiesel (200 ml)+DEE5+Hydrogen 6 lpm	
JFB20+DEE5+H2 8 lpm	Diesel (800 ml)+Juiliflora seed oil Biodiesel (200 ml)+DEE5+Hydrogen 8 lpm	

Source: Authors, (2026).

II.2.1 Uncertainty Analysis

Experimental measurements are intrinsically accompanied by uncertainties that emerge from the precision of instruments, measurement methodologies, and various environmental influences. In the present investigation, an uncertainty analysis was performed for critical measured parameters, which encompass fuel consumption, air flow rate, brake power, and exhaust gas emissions. The aggregate Uncertainty (Uc) for each derived parameter was derived utilizing the root sum square (RSS) technique. Table 4 shows the uncertainties of important measured and computed parameters. Using the relevant equations, the overall combined uncertainty for the entire experimental study was found to be $\pm 1.92\%$, which is within acceptable bounds for engine testing.

$$U_x = \sqrt{\sum_{i=1}^n \frac{(X - X_i)^2}{n(n-1)}} \quad (1)$$

$$x = \sum_{i=1}^n \frac{x_i}{n} \quad (2)$$

$$U_{Es} = \sqrt{(U_\omega x \frac{E_s}{\omega})^2 + (U_T x \frac{E_s}{T})^2} \quad (3)$$

$$U_{m_{fuel}} = \sqrt{(U_{m_i} x \frac{m_{fuel}}{m_i})^2 + (U_{m_g} x \frac{m_{fuel}}{m_g})^2} \quad (4)$$

$$U_{BSFC} = \sqrt{(U_\omega x \frac{BSFC}{\omega})^2 + (U_T x \frac{BSFC}{T})^2 + (U_{m_{fuel}} x \frac{BSFC}{m_{fuel}})^2} \quad (5)$$

$$U_{BTE} = \sqrt{(U_\omega x \frac{BTE}{\omega})^2 + (U_T x \frac{BTE}{T})^2 + (U_{m_{fuel}} x \frac{BTE}{m_{fuel}})^2} \quad (6)$$

$$U_{CO_2} = \sqrt{(\frac{U_{CO_2}}{CO_2})^2 + (\frac{U_{Es}}{E_s})^2} \quad (7)$$

$$U_{HC} = \sqrt{(\frac{U_{HC}}{HC})^2 + (\frac{U_{Es}}{E_s})^2} \quad (8)$$

$$U_{NOx} = \sqrt{(\frac{U_{NOx}}{NOx})^2 + (\frac{U_{Es}}{E_s})^2} \quad (9)$$

$$U_{CO} = \sqrt{(\frac{U_{CO}}{CO})^2 + (\frac{U_{Es}}{E_s})^2} \quad (10)$$

Table 2: Specifications of test engine.

Parameter	Instrument	Range	Accuracy	% Uncertainty
Load	Load Cell	0-50 kg	± 0.1 kg	$\pm 0.2\%$
Speed	Magnetic Pickup	0-9999 rpm	± 10 rpm	$\pm 0.1\%$
Time	Electronic Stopwatch	-	± 0.1 s	$\pm 0.2\%$
Fuel Flow	Burette & Stopwatch	10 cc	± 0.1 cc & ± 0.1 s	$\pm 1.0\%$
Crank Angle	Encoder	0-720°	$\pm 1^\circ$	$\pm 0.1\%$
Cylinder Pressure	Piezo Sensor	0-250 bar	± 0.5 bar	$\pm 0.6\%$
CO	AVL Gas Analyzer	0-15% vol	$\pm 0.02\%$ vol	$\pm 0.15\%$
HC	AVL Gas Analyzer	0-20000 ppm	± 10 ppm	$\pm 0.1\%$
NOx	AVL Gas Analyzer	0-5000 ppm	± 5 ppm	$\pm 0.2\%$
Smoke Opacity	AVL Smoke Meter	0-100%	$\pm 1\%$	$\pm 1.0\%$
Combined Uncertainty				$\pm 1.92\%$

Source: Authors, (2026).

III. RESULTS AND DISCUSSION

For the selected test engine, the investigation with base fuel diesel, Juli Flora biodiesel blend in terms of performance characteristics such as Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC) and emission characteristics such as CO, NO_x, UHC, smoke

III.3.1 Engine Performance Characteristics

III.3.1.1 Brake Thermal Efficiency

The graph shows the brake thermal efficiency at various loads for diesel, Biodiesel blends and biodiesel blends with DEE additive in Figure 5. Initially the BTE for the JFB20 decreases by 4% than the diesel. It is because of the reason that the juliflora oil has high viscosity, high density and low volatility gives poor atomization, bigger droplets and slow evaporation. When DEE is added as additive with JFB20 blend there is slight increase in BTE but not matching the diesel. While enriching the hydrogen along the JFB20DEE5 varying flow rates such as 4 lpm, 6 lpm and 8 lpm the BTE is increased to 2%, 5.1% and 10 % than the diesel. As the load increases the brake thermal efficiency also increases for biodiesel blends of JFB20but when hydrogen is added with the blends it is observed that the brake thermal efficiency has been increased by 10% for JFB20DEEH8 than diesel at higher load. From the above result, it is understood that due to the sufficient amount of oxygen content in the biodiesel, the combustion rate is higher which gradually increases the brake thermal efficiency for all the tested blends. Hydrogen enrichment increases BTE because it converts slow diffusion combustion of juliflora biodiesel into rapid premixed combustion, advancing heat release towards TDC, increasing peak cylinder pressure, reducing combustion duration, and improving fuel utilization efficiency.

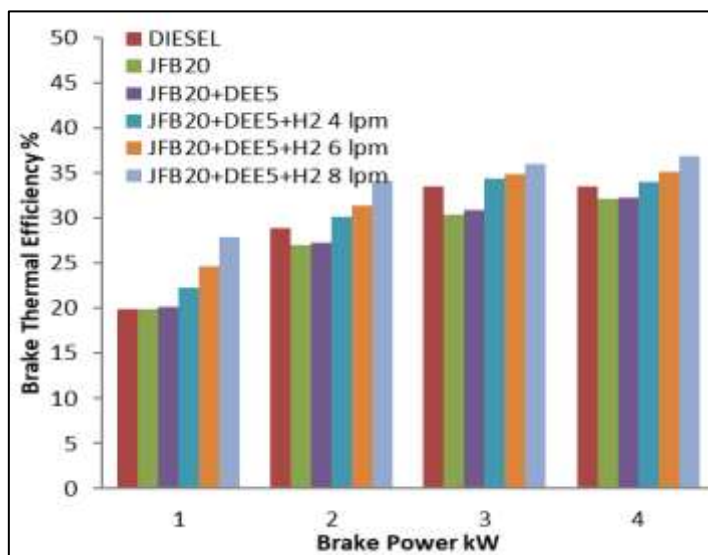


Figure 5: Variation in BTE.
Source: Authors, (2026).

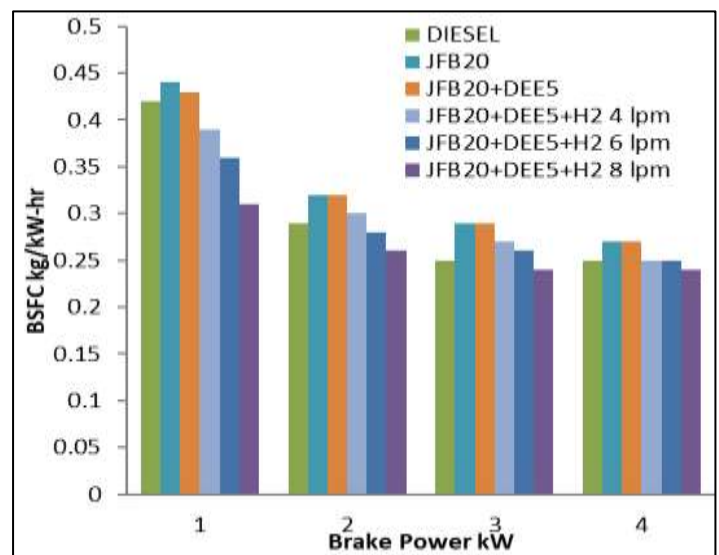


Figure 6: Variation in BSFC.
Source: Authors, (2026).

III.3.1.2 Brake Specific Fuel Consumption

The values of different Brake specific fuel consumption for various loads of diesel and biodiesel blends are shown in Figure 6. From the graph, the SFC decreases for increasing the loads for the all the JFB20 blends. Compared to diesel the JFB20 blend give more fuel consumption than diesel and also it continues in the case of the blend when DEE is added. It is noticed that when the JFB20DEE5 is enriched by hydrogen with varying flow rates the BSFC is decreased. It is observed that at full load the BSFC decrease by 4% for the JFB20DEE5H8 blend than pure diesel. The reduction in BSFC with 8 lpm hydrogen enrichment is attributed to diesel substitution, improved premixed combustion, enhanced oxidation of juliflora biodiesel droplets, and higher combustion efficiency, which allows the engine to produce the same brake power with a lower biodiesel consumption rate. Hydrogen has very high calorific value and participates in combustion, so part of engine load is carried by hydrogen instead of biodiesel. Also, its high flame speed improves combustion and reduces late burning losses. Therefore, less biodiesel is required to produce the same brake power, leading to lower brake specific fuel consumption

III.3.2 Emission characteristics

III.3.2.1 Carbon monoxide (CO) emissions

The emission of Carbon monoxide from the biodiesel blends and the pure diesel are noted and its variations against the different loading conditions are plotted in the graph as depicted in Figure 7. CO emission for the JFB20 is increased for when the load increases around 5% and 11% for half load and full load conditions respectively. This may be due to poor atomization as the Juliflora oil has higher viscosity and incomplete mixing of particles. When the blend is enriched by hydrogen for the 4 lpm, 6 lpm and 8 lpm, the CO emission is considerably decreased for the half load and full load conditions as 9%, 13% and 17% respectively. It is clearly observed that, the CO emission is less for the higher loads for all tested blends.

The JFB20DEE5H8 gives less CO emission of 17% at full load than diesel. The reason is when hydrogen is added with biodiesel it produces faster combustion burns very quickly and completely, enhances the oxidation reactions converting CO into CO₂, improves the overall efficiency and reduces the unburnt fuel [19].

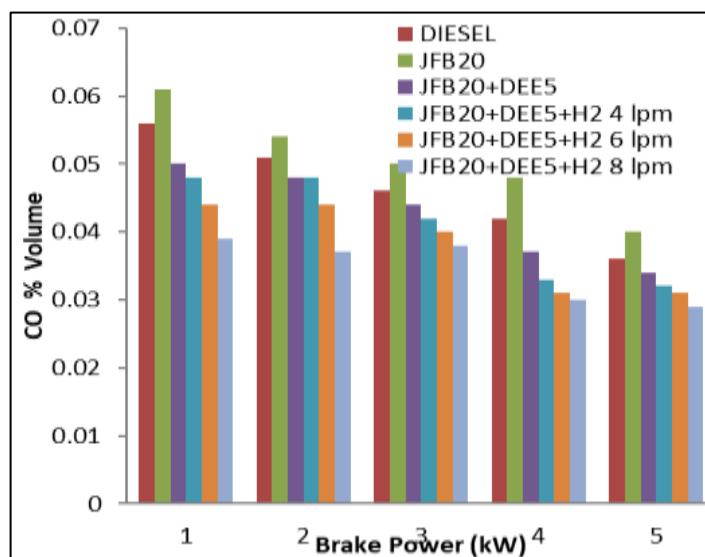


Figure 7: Variation in CO emission.

Source: Authors, (2026).

III.3.2.2 Unburned hydrocarbon emissions (UBHC)

The another important emission characteristics of the tested oil blends is the Unburned hydrocarbon emissions (UBHC) that are measured against at different load conditions are plotted as shown in Figure 8. From the graph it is noticed that for the juliflora blend (JFB20) HC emission is slightly increases from 3 % to 9 % for the half load and full loads than the diesel. It is because the biodiesel oil has volatile and inadequate atomization of fuel. It is observed that, the UBHC emissions are decreases when the Diethyl Ether is added to blend it gives 9% HC reduction as the load increases. For the blends JFB20DEE5H4, JFB20DEE5H6 and JFB20DEE5H8, UBHC is decreasing by 9% to 28% at full load than diesel. Hydrogen stabilizes combustion by shorter ignition delay, more controlled premixed combustion and less fuel escaping unburned [20]. HC emissions decrease with hydrogen enrichment as the hydrogen contains no carbon and promotes faster, more complete combustion, improving oxidation of Juliflora biodiesel.

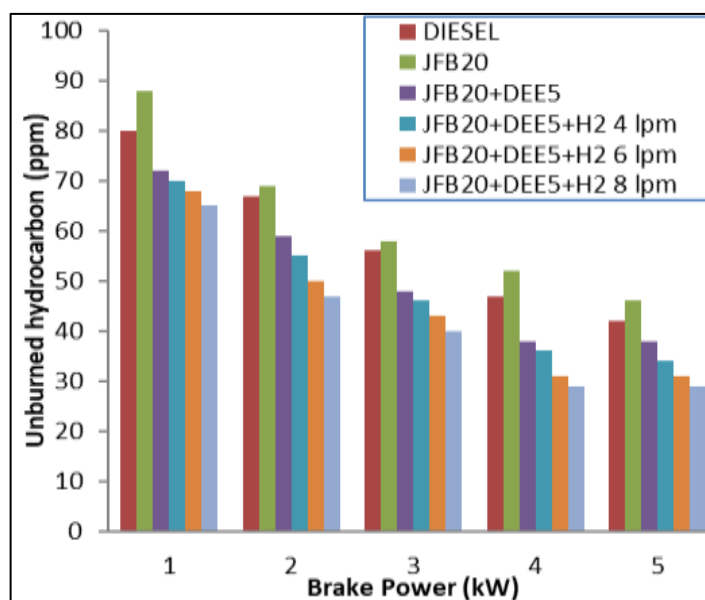


Figure 8: Variation in UBHC.

Source: Authors, (2026).

III.3.2.3 Oxides of nitrogen (NO_x) emissions

The NO_x is an emission which should be controlled during the combustion of fuels. The values for different blends at varying load conditions are measured are plotted in graph depicted in Figure 9. In general, the NO_x emissions are increasing as the percentage of load increases. In-cylinder temperature, reaction time and availability concentration of oxygen content in the biodiesel are the main reasons for the formation of NO_x. It is observed that, the NO_x emissions are high for pure diesel. Increasing load gradually increases the NO_x emission for all tested fuels.

NO_x formation depends mainly on high combustion temperature and oxygen concentration. According to the Zeldovich mechanism, at temperatures above 1800 K, nitrogen reacts with oxygen to form nitric oxide. Therefore, faster combustion, high flame speed, higher peak temperature and more oxygen in biodiesel or hydrogen-enriched engines lead to increased NO_x formation [21], [22].

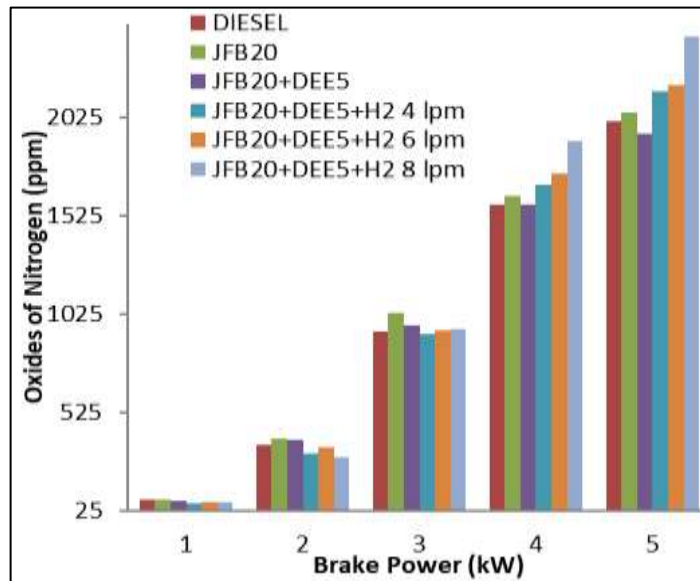


Figure 9: Variation in NO_x.

Source: Authors, (2026).

III.3.2.4 Smoke emissions

The smoke emission is measured and the variations against the different loading conditions are plotted in graph as depicts in Figure 10). From the graph, it is observed that, smoke opacity increases in JFB20 blend mainly because of higher viscosity and poor atomization compared to pure diesel. It leads to incomplete combustion and formation of soot particles. Though the biodiesel contains oxygen, the poor spray characteristics and slower evaporation can increase smoke under certain engine conditions [23]. The Diethyl ether slightly reduces the smoke to 1% than the diesel. The better reduction smoke is achieved by the enrichment of hydrogen with the JFB20DEE5 at 4 lpm, 6 lpm and 8 lpm and reduces by 5%, 8% and 11% for the blends JFB20DEE5H4, JFB20DEE5H6 and JFB20DEE5H8 respectively at full load condition than the pure diesel.

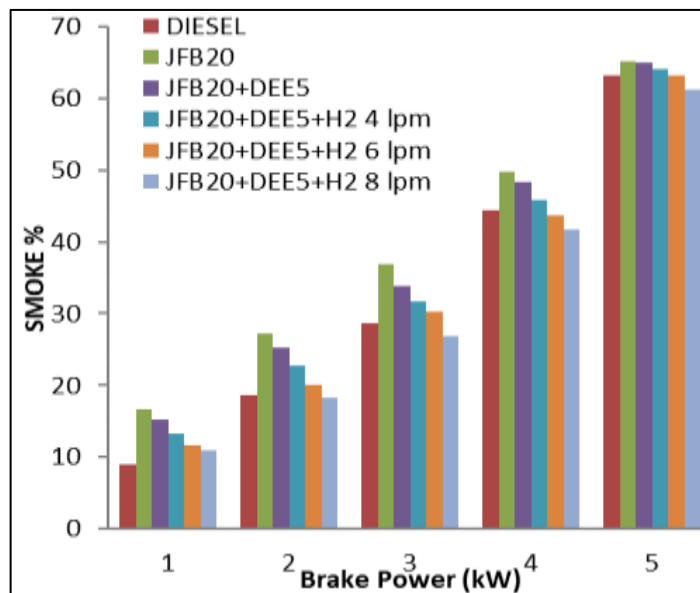


Figure 10: Variation in Smoke emission.

III.3.3 Combustion characteristics

III.3.3.1 In-cylinder pressure

The combustion characteristics of the fuel being consumed are the main determinants of the pressure and net heat release rates produced during combustion in internal combustion engines. During combustion, the engine's JulifloraB20 and JulifloraB20 along with 5%DEE at different hydrogen flowrates at full load, which results in variations in the in-cylinder pressure. It is clear that both JulifloraB20 and Juliflora B20 along with 5%DEE and the hydrogen-enriched JulifloraB20 biodiesel mix generated increased cylinder pressure when compared to pure diesel fuel (Refer Figure 11).

A larger calorific value of the hydrogen-enriched fuel mix with greater density, more fuel injection, an earlier start to the combustion process, and better ignition quality can all increase in-cylinder pressure and combustion speed. Figure 8 shows the combustion cylinder pressures for different fuel blends and hydrogen flow rates at 100% load. Specifically, the comparison is drawn between pure diesel, Juliflora B20 and various hydrogen blends, ranging from 4 lpm to 8 lpm hydrogen flow. At full load condition the Jfb20 the cylinder pressure decreases to 65.33 bar from the 68.27 bar which is the cylinder pressure achieved by the pure diesel. It is reduced by 7.7% than that of diesel. While adding the 5% of Diethyl Ether(DEE) the cylinder increases by 1.2 % than the diesel. It is observed that the hydrogen enriched JFB20 blends with 4 lpm, 6 lpm and 8 lpm attained the cylinder pressures 70 bar, 72.5 bar and 75.3 bar respectively. The addition of hydrogen significantly impacts the combustion process, as hydrogen has a higher energy content and burns faster than conventional fuels, leading to a more intense combustion cycle and increased pressure. At the highest hydrogen flow rate 8 lpm (JFB20DEE5H8) the cylinder pressure is notably higher, reflecting a more efficient and potentially more powerful combustion. The data specifically highlights that at 100% load, an 8 lpm hydrogen flow produces an approximate 10.3% increase in cylinder pressure compared to using diesel fuel. This result underscores the role of hydrogen in enhancing the combustion characteristics of biodiesel blends, improving performance by increasing the cylinder pressure, which may contribute to better power output and potentially reduced emissions, given hydrogen's cleaner combustion properties [24], [25]. This suggests that hydrogen blending can be an effective strategy for optimizing engine performance and fuel efficiency, especially when considering the transition to greener energy sources in the automotive and industrial sectors

III.3.3.2 Heat Release Rate

An analysis of the engine's combustion status is conducted using the HRR. Because the injected fuel had a higher mass concentration than diesel fuel, the maximum HRR value for JFB B20 blends developed. The rate of heat release from biodiesel blends was greater than that of regular diesel fuel due to their shorter ignition delay period. Additionally, the biodiesel fuel blends showed a greater peak rate of heat release. The diffusive combustion phase revealed a little reduced heat release when utilizing biodiesel blends as fuel as opposed to regular diesel. This may be because biodiesel has a larger concentration of oxygen, which eventually results in a longer burning phase. In this figure 12, the plots of Heat Release Rate (HRR) for various fuel blends at both 100% load are shown, highlighting the effect of hydrogen addition to JFB20, a hydrogen-free biodiesel made from Juliflora oil. Hydrogen addition at all load conditions exhibited marked increase in HRR values, which infer better combustion. At 100% load, the HRR for JF B20 reaches 32.22 J/°CA, and when adding 5% DEE it increases to 35.9 J/°CA.

For 8 lpm hydrogen is introduced, this value goes up to 41.74 J/°CA-an increase of 3.41 J/°CA or an enhancement by 9%. The high flame speed and energy density of hydrogen improve overall combustion efficiency, resulting in higher heat release and pressure. This also signifies that combustion is more complete with hydrogen leading to enhanced engine performance [21], [25]. The continuous increase in HRR for load conditions, especially at the highest hydrogen flow of 8 lpm, brings to focus the advances that could be made looking at hydrogen as a safe fuel additive aimed at improving biodiesel performances. Not only this enhancement pertains to power generation, but it may also help in optimizing fuel usage and reducing emissions, with hydrogen being naturally environmentally-friendly. With a fair increase in HRR at both loads, hydrogen blending stands as one of the encouraging strategies for optimizing biodiesel combustion and addressing the technological concerns for better engine performance, which respects the wish of diminishing the environmental impact of conventional fuels.

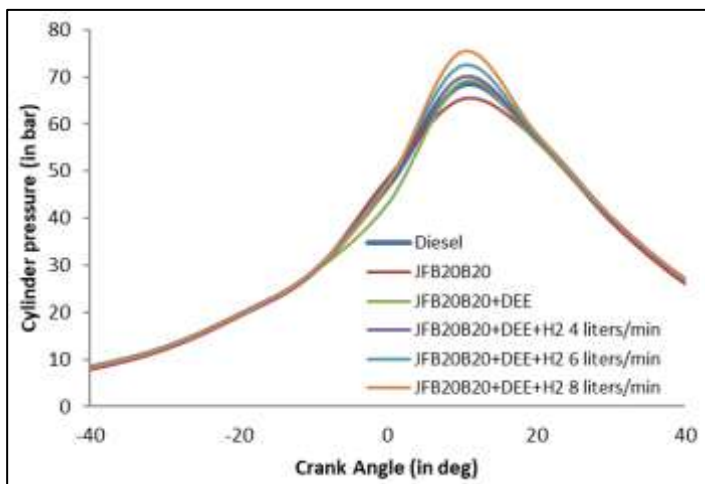


Figure 11: Variation in Incylinder pressure.
Source: Authors, (2026).

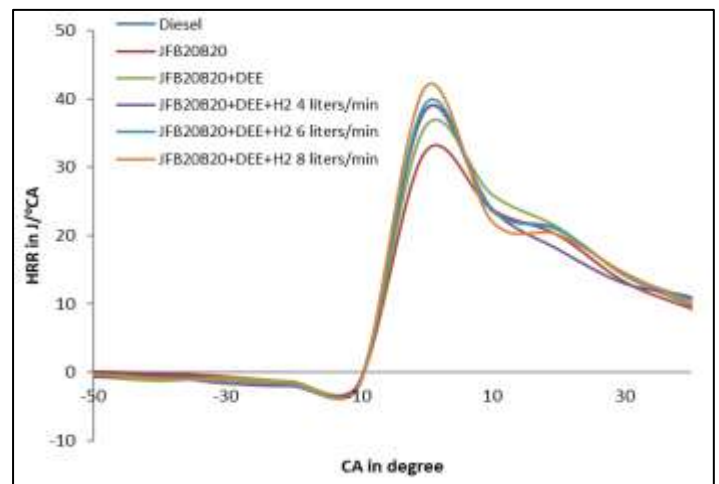


Figure 12: Variation in Heat release rate
Source: Authors, (2026).

IV. CONCLUSIONS

The above investigation describes the effect of enrichment of hydrogen with Juli Flora biodiesel in addition of Diethyl Ether with Diesel. The present investigation evaluated the performance, emission and combustion characteristics of a CI engine fuelled with Juliflora biodiesel blend (JFB20), JFB20 with 5% Diethyl Ether (DEE), and hydrogen-enriched JFB20DEE5 at varying hydrogen flow rates (4, 6 and 8 lpm). The results indicate that JFB20 exhibits slightly lower brake thermal efficiency (BTE) compared to diesel due to its higher viscosity, density and lower volatility, which adversely affect atomization and evaporation. The addition of 5% DEE moderately improves BTE owing to its high cetane number and better volatility. Significant enhancement in performance is observed with hydrogen enrichment. At 8 lpm hydrogen flow (JFB20DEE5H8), BTE increased by 10% compared to diesel at full load.

This improvement is attributed to hydrogen's high calorific value, high flame speed and rapid premixed combustion, which advance heat release towards TDC, increase peak cylinder pressure and reduce combustion duration. Brake Specific Fuel Consumption (BSFC) decreases with increasing load for all blends. Although JFB20 and JFB20DEE5 show slightly higher BSFC than diesel, hydrogen enrichment markedly reduces fuel consumption. At full load, JFB20DEE5H8 achieved a 4% reduction in BSFC compared to diesel. This reduction is mainly due to partial diesel substitution by hydrogen, improved oxidation of biodiesel droplets, enhanced combustion efficiency and reduced late burning losses. In terms of emissions, JFB20 shows a marginal increase in CO and UBHC emissions at higher loads due to incomplete combustion arising from poor spray characteristics.

However, hydrogen enrichment substantially reduces CO (17%) and UBHC (up to 28%) at full load compared to diesel. The carbon-free nature of hydrogen, along with faster and more complete combustion, enhances oxidation reactions and minimizes unburnt fuel emissions. Smoke opacity, which slightly increases for JFB20 due to higher viscosity and poor atomization, is effectively reduced with hydrogen addition, achieving up to 11% reduction at 8 lpm compared to diesel. NO_x emissions increase with load for all tested fuels. The rise in NO_x with hydrogen enrichment is mainly attributed to higher in-cylinder temperature, increased oxygen availability and faster combustion, consistent with the Zeldovich thermal NO_x formation mechanism. Although hydrogen improves combustion efficiency, the associated rise in peak temperature promotes NO_x formation. Combustion analysis further supports these findings.

Hydrogen-enriched blends demonstrate higher in-cylinder peak pressure and heat release rate (HRR) compared to diesel and JFB20. At full load, JFB20DEE5H8 produced a 10.3% higher cylinder pressure and enhanced HRR, confirming improved combustion intensity and energy utilization. The higher flame speed and energy density of hydrogen lead to a more rapid and efficient combustion process. Overall, the study demonstrates that hydrogen enrichment of JFB20DEE5H8 significantly enhances engine performance and combustion characteristics while reducing CO, UBHC and smoke emissions. Although NO_x increases due to elevated combustion temperature, the combined use of Juliflora biodiesel, DEE and hydrogen presents a promising strategy for improving CI engine efficiency and reducing carbon-based emissions. With appropriate NO_x control techniques, hydrogen-assisted biodiesel blends can serve as a viable and sustainable alternative fuel for future diesel engine applications.

V. AUTHOR'S CONTRIBUTION

Conceptualization and Methodology: D Saravanan and D. Balaji

Investigation, Writing – Original Draft: D Balaji and V. Hariram

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Supervision, Approval of the final text: V Hariram

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