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Dual-Fuel Engine Behaviour with *Juliflora* Biodiesel and Hydrogen: A Study on Performance and Emission Enhancement

Satish Kumar Kuruba and R. L. Krupakaran*

Department of Mechanical Engineering, Mohan Babu University, Tirupati - 517102, Andhra Pradesh, India; krupakaran1305@gmail.com

Abstract

The present investigation aims to examine the influence of Juliflora biodiesel blends along with hydrogen at different flow rates of 6 lpm and 8 lpm on a dual-fuel engine at different load conditions. The transesterification method was adopted to produce Juliflora biodiesel, and with the aid of a mechanical stirrer, Juliflora biodiesel-diesel blends (JB20) were prepared. To analyse the parameters of an engine, experiments were conducted using diesel, JUB20, and JUB20 with hydrogen at 6 lpm and 8 lpm on a diesel engine. The obtained results show that BTE was enhanced by 4.57% and 8.43% by using JUB20 fuel with hydrogen at 6 lpm and 8 lpm. In addition, the exhaust parameters such as CO emissions were lower by 5.28 %, CO_2 emissions by 9.86%, and HC emissions by 10.71% for JUB20 fuel with a hydrogen flow rate of 8 lpm. Further, NOx emissions were marginally enhanced for the fuels such as JUB20, JUB20 fuel with hydrogen addition at both flow rate conditions. The study concludes that hydrogen supplementation in a Juliflora biodiesel dual-fuel engine offers a promising route to cleaner and more efficient energy use, contributing to both environmental sustainability and effective waste biomass utilization.

Major Findings: *Improved brake thermal efficiency while significantly reducing major emissions.*

Keywords: *Emission Parameters, Hydrogen, Juliflora Biodiesel, Performance*

1.0 Introduction

The progress of renewable fuels from biomass is currently a critical component of future energy due to the depletion of petroleum fuels. Nonetheless, the population's rapid growth has resulted in a huge rise in both energy consumption and demand. In both the transportation and agricultural sectors, diesel engines are crucial, and with the technological and innovative advancements, there has been an increase in the dependency on petroleum products[1]. The primary cause of urban air pollution and the actual source of greenhouse gases known as ozone-depleting substances (GHGs), non-renewable energy sources are also thought to be the primary cause of global environmental change. Biofuels emit lower emissions of greenhouse gases and are renewable. They are being utilized more frequently as a substitute fuel for petroleum-based fuels. Most of the researchers have concluded that biofuels are a viable alternative to internal combustion engines. Ramalingam *et al.*[2] investigated the suitability of citronella biodiesel in different (B20, B40, and B60) fractions on a diesel engine. They concluded that using citronella blends shows lesser BTE values than diesel, while the B20 blend demonstrated superior efficiency. The results show that B20 fuel claimed a 1.47% lower BTE and a 2.7% greater fuel consumption. According to the combustion analysis, citronella fuel significantly reduced Ignition Delay (ID) while improving

*Author for correspondence

cylinder pressure (CP), EGT, and HRR. Nicholas *et al.*[3] conducted engine tests to illustrate the process of biodiesel making from *Pongamia* oil affected a diesel engine's parameters analysis. They observed that pongamia biodiesel exhibits a marginally higher brake-specific fuel consumption than diesel fuel. In addition, Smoke, CO, NO_x and HC tailpipe emissions were diminished by 26%, 25%, 6%, and 46%, respectively. Perumal and Ilangkumaran[4] analyzed the effect of diesel and biodiesel blends (*C. viscosa* biodiesel) experimentally in a diesel engine. They observed that *C. viscosa* biodiesel was used in diesel engines, greenhouse gases such as CO and HC were decreased by 30% and 20%, respectively. Further, NO_x emissions and smoke levels rose to 6.04% and 9.03%, respectively. Maximum peak pressure and HRR were obtained for the B20 blends of *C. viscosa* compared to diesel. Tuccar and Uludamar[5] evaluate the diesel engine characteristics with hydrogen-enriched POB (pomegranate biodiesel) using a diesel engine. It is observed that POB fuel reduces CO emissions by 16% with the POB fuel and further reduces by 6% with 5 lpm hydrogen and proving as a promising fuel. However, engine performance is evident that using POB lowers engine power and raises nitrogen oxide emissions by 25%, although hydrogen enrichment triggers NOx emissions slightly (1%). Kursam and Kumar[6] demonstrated experiments on the VCR diesel engine using fuel samples such as diesel, KOME (Karanja Oil Methyl Ester) Blend B20, and KOME Blend B20 with various hydrogen flow rate conditions. They found maximum BTE (33.02%) at CR-18 and 220 bar IOP for test fuel of B20 with 15 lpm of hydrogen, and B20 with 15 lpm of hydrogen decreases BSFC by 40.42%. Further, the lowest CO and CO_2 emissions were recorded, and they were 89% and 72% lower than those of the pure diesel mode for B20+15 lpm at 220 bar of pressure. The oxides of nitrogen emissions, which are measured at 220 bar IOP and drop by 2 to 4% at that level, were marginally reduced and increased with the rising CR. Temizer and Cihan[7] concluded that flame velocity increased and the burning time decreased when hydrogen fuel was added to diesel fuel. They found that the induction of hydrogen fuel raised the temperatures of the combustion chambers, and that the temperature in the MCC type geometry affected the NO emissions more than in the SCC chamber geometry. Further, by the addition of hydrogen fuel with diesel fuel, CO emissions were reduced. Aydin and Safa[8] studied the impact of Compressed Natural Gas (CNG) combined with waste frying oil biodiesel (WFOB) on a diesel engine's emissions and performance at 3000 rpm. They observed that increasing CNG substitution ratios enhances 12.58 % of BSFC and decreases BTE up to 17.97%. In addition, NOx emissions were increased with WFOB blends up to 2.75% but lowered in dual fuel mode by 13.7%. The CO emissions are reduced by 4.76% with the pilot injection of WFOB blends and increased with the inclusion of CNG. A noticeable reduction in smoke opacity was identified with the usage of both CNG and WFOB blends. AlGhafis *et al.*[9] studied the effect of variation in injection timing (IT) (33°, 28°, 23° and 18°) and influence of vibration over diesel engine. They found that BTE rises by 3.7% when compared to pilot fuel and reached its maximum at CA 280 BTDC for B20 + 10 lpm of hydrogen when compared to pure diesel. BSFC was lower for B20 + 10 lpm of hydrogen at same CA and decreased by 3.5% compared to pilot fuel. In addition, 17.09% of CO was decreased as compared to pilot fuel. They also observed that NOx were increased up to 19.7% compared to pilot fuel. When comparing to B20 + 10 lpm of hydrogen fuel to pure diesel at IT CA 28° BTDC, it was also discovered that the combustion and vibration factors were better and lower, respectively. Baligidad *et al.*[10] investigated that influence of Induction of acetylene into a diesel-corn biodiesel blend at varying flow rates and at 50% and 100% loads. They revealed that the maximum BSFC was 7.9% at 50% load for the B20 blend with acetylene and with the induction of acetylene in to the B20A25 blend the peak BTE, *i.e.*, 23.9% was observed. In addition at 50% and 100% load conditions, compared to diesel fuel, NOx emissions from B20 fuel were 9% and 17% higher, respectively. Additionally, the accumulation of acetylene, NOx emission was further enhanced by 3% compared to all fuels. The maximum CO_2 emission was obtained for B20A25 of 13.5% at 100% load condition[12]. Sudarmanta *et al.*[11] concludes that the impact of PIT using CPO biodiesel fuel on improving engine performance and lowering emissions. On a DF engine, the PIT parameter was adjusted at 2-degree intervals between 11° and 19° BTDC at various engine loads. The DF engine's brake thermal efficiency increased by 8.87%, cylinder pressure increased by 21.46%, and HRR increased by 7.34% when the pilot injection timing was advanced to 15° BTDC at high load. At the same time, the SFC reduced by 9.43%. Similarly, CO emissions were

decreased by 43.85% and HC emissions decreased by 25.33%. When the dual fuel engine's pilot injection timing was adjusted to 19° BTDC at low load, the SFC was dropped by 1.37% while the brake thermal efficiency, cylinder pressure, and HRR increased by 1.28%, 23.76%, and 23.80%, respectively. Similar reductions were observed in CO emissions of 26.26% and HC emissions of 19.43%[14]. Mahdi *et al.*[12] demonstrate that while hydrogen enrichment and HHO both enhance engine performance and fuel economy, hydrogen exhibits a more notable decrease in toxic pollutants such as Carbon Monoxide (CO) and hydrocarbon (HC) emissions. Diesel engines with hydrogen and HHO enrichment have better combustion properties, which results in cleaner and more effective fuel use. The study comes to the conclusion that although hydrogen and HHO can both improve the performance of diesel engines, hydrogen has a higher potential for significant emissions reductions. Mustafa *et al.*[13] conducted engine tests using biodiesel, biodiesel-H_2 and biodiesel-ethanol-H_2 in a 4-stroke, 4-cylinder diesel engine at a constant 1750 rpm engine speed and they found that when engine load increases, BSFC drops by more than 20%. Furthermore, the maximum BSFC in BD70E30 gasoline was observed to be 373 g/kWh. Cylinder gas pressure increased from 80 bar to over 125 bar as a result of an increase in engine load. Under specific test settings, it was demonstrated that blended fuels increase cylinder gas pressure and regulate the maximum pressure rise rate by decreasing ignition delay. Blended fuels were found to considerably lower HC and CO_2 emissions when compared to biodiesel fuel, but to marginally increase NO emissions. Tamilselvan *et al.*[14] investigated the performance, emissions, and combustion properties influence on diesel engines using n-pentanol and diesel blends are affected by a 4 LPM hydrogen (H_2) enrichment. The results show that by lowering fuel consumption (10%) and raising thermal efficiency (4%) injecting H_2 considerably improves engine performance. On the other hand, increased H_2 content usually results in increased NOx emissions[18]. *Juliflora* is underexplored despite being abundant and invasive in many regions. While hydrogen enrichment in diesel engines has been studied, there's limited data on hydrogen with *Juliflora* biodiesel blends, especially in real-world conditions. From the literature we concluded that investigation on the effects of Juliflora biodiesel blend along with hydrogen addition on the emission and performance parameters in an unmodified diesel engine.

2.0 Fuel Preparation and Properties

Prosopis Juliflora seeds were purchased from the local market, Tirupathi, India and oil from the seeds was obtained by adopting the drying process and oil expeller mill. The plant oil used to make *Juliflora* biodiesel is renewable and may be harvested or grown sustainably. In the event of spills or leaks, *Juliflora*'s biodiesel is safer for the environment and biodegradable. When *Juliflora* biodiesel is burnt instead of regular diesel, less carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons, and particulate matter are released. For producing Juliflora biodiesel transesterification process was selected by using solvents like methanol, NaOH. Using a magnetic stirrer, one litre of *Juliflora* oil was heated to 75°C in a round-bottom flask to remove any remaining moisture. A methanol to oil molar ratio of 6:1 was achieved by using 200 ml of methanol, and it was used to dissolve the catalyst NaOH in a different jar, which was then added to the round-bottom oil flask while being constantly stirred for one hour. The mixture was permitted to settle for eight hours, and the final products of the process were glycerin and methyl ester of *Juliflora* oil, were obtained. In the final stage, biodiesel, alcohol, and some soap in the top layer which were formed and separated. The Juliflora biodiesel was blended with diesel fuel in the volumetric approach (*i.e.*, 200 ml of *Juliflora* biodiesel and 800 ml of diesel) to prepare JUB20 biodiesel. The fuel properties for the diesel and JUB20 fuel were determined as per ASTM standards and tabulated in Table 1.

Table 1. Properties of fuel samples

Parameters	Diesel	JUB20
Density @15°C (kg/m^3)	840	846.8
Flash Point (°C)	52.5	69
Fire Point (°C)	58	78
Kinematic Viscosity @ 40°C (centistokes)	3.24	3.68
Gross Calorific Value (kJ/kg)	44,500	40,690
Cetane Index	51.6	52.85

3.0 Experimental Setup and Procedure

The engine tests were conducted on a Kirloskar make, single cylinder, water cooled, four stroke DI diesel engine with diesel fuel, JUB20, JUB20+Hydrogen 6 LPM and JUB20+Hydrogen 8 LPM at 1500 rpm engine speed and 0 %, 25%, 50%, 75% and 100% engine loads. The schematic diagram of a diesel engine is shown in Figure 1. Figure 2 shows a flow diagram of the work. The eddy current dynamometer with load cell arrangement was used for applying the various loads. The hydrogen gas was supplied from the cylinder and sent into the inlet manifold with the air flow with the help of a hydrogen cylinder, flame arrester and flame trap. A hydrogen flow meter was adopted to measure the hydrogen gas flow rate. The

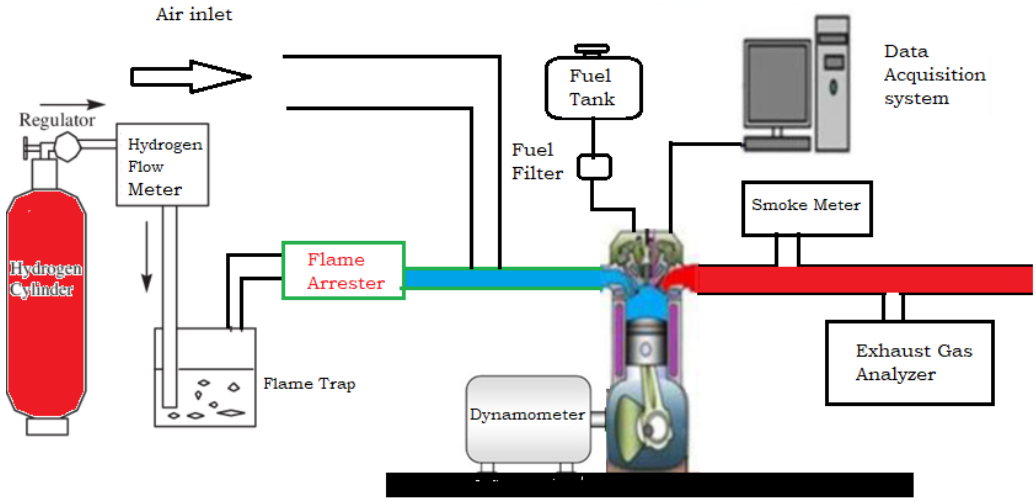


Figure 1. Schematic diagram of a diesel engine.

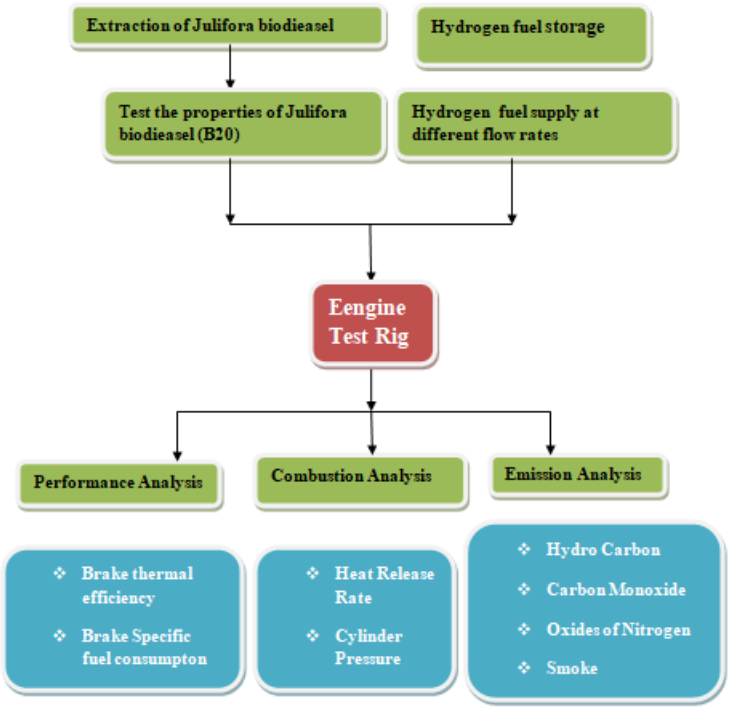


Figure 2. Flow diagram of the work.

AVL make exhaust gas analyser was used to determine the CO, CO_2, HC and NO_x emissions. The AVL smoke meter was also used to determine the smoke opacity of a diesel engine. The specifications of a diesel engine and measuring instruments were shown in Tables 2-4. A comparison of previous work was given in Table 5

Table 2. Engine specification

Parameters	Specifications
Engine Make	Kirloskar TAF1
Type	Vertical diesel engine, four-stroke
Number of Cylinders, Fuel	One, Diesel
Cooling System	Air cooled
Ignition system	Compression ignition
Rated brake power	4.4 kW @ 1500 rpm
Displacement	661 cc
Bore and stroke	87.5 mm and 110 mm
Compression ratio	17.5:1
Injection timing	23° bTDC (rated)
Injection pressure	200 bar

Table 3. Specification of the exhaust gas analyser

Make	AVL Digas 444
Measuring parameter	CO, HC, CO_2, NOX, O_2, λ
Measuring method	CO, HC, CO_2 – NDIR method NOX, O_2 – Electrochemical method
Measuring range and resolution	CO – 0…10% vol and 0.01% HC – 0…20000 ppm and 1ppm vol CO2 – 0…20 % vol and 0.1% NOX – 0…5000 ppm vol and 1 ppm vol λ – 0…9.999 and 0.001%
Response time	Within 15 s
Warming up time	About 7 min
Connector gas in	About 180 l/h
Operating temperature	5….50 oC
Relative humidity	≤ 95%, non-condencing
Power consumption	About 25 W
Voltage	22 V DC
Interfaces	RS 232 communication cable, printer

Table 4. Specification of Bosch smoke meter

Type and make	T1 diesel tune, 114-smoke density tester T1 transervice
Piston displacement	330 cc
Stabilisation time	2 min
Range	0 – 10 Bosch Smoke Number
Minimum time period	30 cc
Calibrated reading	5.0 + 0.2

4.0 Results and Discussions

4.1 Performance Characteristics

4.1.1 Brake Thermal Efficiency (BTE)

The BTE results for diesel, JUB20, and JUB20 with 6 lpm and 8 lpm with brake power as shown in Figure 3. BTE was improved with an increase in BP for all the fuel samples because of lesser losses at peak loads. Due to the higher calorific value of diesel shows higher BTE than the JUB20 fuel at all loads. The BTE for the JUB20 fuel was reduced by 5.8% compared to the diesel fuel due to the higher density and low calorific value of biodiesel[15]. Hydrogen utilization in the engine along with JUB20 fuel with 6 lpm and 8 lpm enhances the BTE by 4.57% and 8.43%, respectively, due to increased combustion with a high diffusivity nature and reduced quenching distance is possible with hydrogen.

4.1.2 Brake Specific Fuel Consumption (BSFC)

The BSFC results for diesel, JUB20, and JUB20 with 6 lpm and 8 lpm with brake power as shown in Figure 4. Because of the higher density of JUB20 fuel, discharging more fuel for the same power output increases the specific fuel consumption compared to diesel[16]. In addition with the supply of hydrogen at 6 lpm and 8 lpm reduces the fuel consumption by 3.8%, 7.8%, respectively because it produces more power and uses less fuel when more hydrogen and air are introduced into the combustion chamber, supplying fuel to the cylinder with a more uniform mixture prior to fuel injection.

Table 5. A comparison of previous literature and its findings summary

Researcher and used fuel	Engine used	Operating condition	Summary
Agarwal *et al.* [21] Mahua raw oil. Progress in Energy and Combustion Science. 2007; 33(3):233-271.	Kirloskar, single-cylinder 4-stroke diesel engine, 4 kW	Blend 10, 20, 30%, IP200bar	30% gave max efficiency compared to 10 and 20%
Dhinesh *et al.* [22] Cymbopogon flexuosus. Energy Conversion and Management. 2016; 117:466-474	Kirloskar, single cylinder 4-stroke diesel engine, 5KW	*Cymbopogon flexuosus* biofuel was blended with diesel fuel in various proportions on a volume basis, namely 10, 20, 30, 40, and 100	Among various blends, the Fuel blend of *Cymbopogon flexuosus* biofuel 20% + diesel 80% fuel profile stayed close to diesel fuel, resulting in higher thermal efficiency and lower hydrocarbon, carbon monoxide, and smoke emissions.
Annamalai *et al.* [23] Lemongrass Oil (LGO) emulsion fuel Energy Conversion and Management. 2016; 123(1):372-380.	Kirloskar, single-cylinder 4-stroke diesel engine, 5 kW.	Cerium oxide (CeO_2) nanoparticle (30 ppm) as an additive mixed with biodiesel	The engine performance could also be increased due to the addition of CeO_2 nanoparticles.
Nandagopal.[24] *Calophyllum inophyllum* biodiesel. Energy Conversion and Management. 2017; 146:8-19.	Kirloskar, single-cylinder 4-stroke diesel engine, 5 kW.	Influence on the effect of zinc oxide and titanium dioxide nanoparticles as an additive-50 ppm and 100 ppm concentrations of titanium dioxide and zinc oxide	The doping of nanoparticles with biodiesel has a very good effect on performance characteristics, with notable improvement in performance and minimum emissions.
Krupakaran.[15] Hydrogen and acetylene gas are injected with an enriched *Jojoba* biodiesel blend. International Journal of Hydrogen Energy. 2024; 50:502-523.	Kirloskar, single cylinder 4 stroke diesel engine, 5 kW,	Conducted an experiment on hydrogen and acetylene gas injected with enriched Jojoba biodiesel blend	Increased engine performance and reduced emissions.

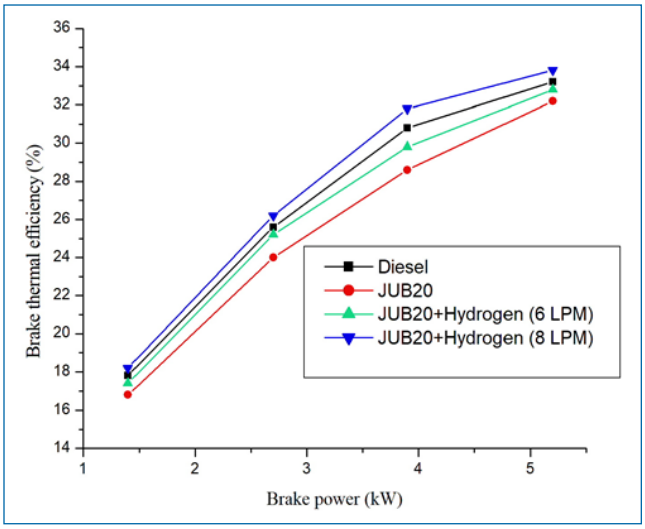


Figure 3. Variation of BTE versus brake power.

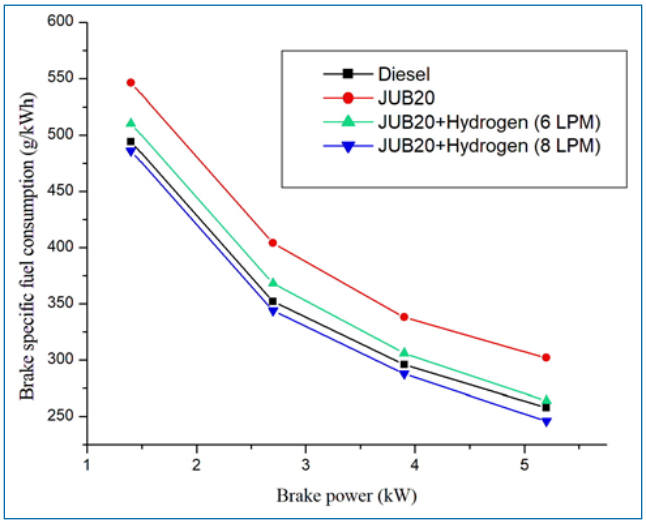


Figure 4. Variation of BSFC versus brake power.

4.2 Emission Characteristics

4.2.1 CO Emissions

Figure 5 depicts the variation of CO emissions for the diesel, JUB20 and JUB20 with hydrogen at 6 lpm and 8 lpm at different loads. It is concluded that CO emissions for the JUB20 fuel slightly reduce because biodiesel contains more oxygen (O_2) content causes lower CO emissions will eventually arise from improved carbon combustion brought about by a higher oxygen content[17]. As a result of hydrogen enrichment, CO emissions showed a declining trend of 3.6% and 5.28% with the addition of 6 and 8 lit/min of hydrogen. The hydrogen particles produce OH molecules with the help of oxygen contained in the air, and these molecules trigger the formation of lesser CO emissions.

4.2.2 CO_2 Emissions

Figure 6 shows the variation of CO_2 emissions for the diesel, JUB20 and JUB20 with hydrogen at 6 lpm and 8 lpm at different load conditions. The obtained results show that JUB20 fuel contains higher oxygen content and burns carbon more quickly, which subsequently leads to higher CO_2 emissions compared to the diesel fuel. The addition of hydrogen along with JUB20 fuel at various flow rates, *i.e.*, 6 lpm and 8 lpm, reduces the CO_2 emissions by 3.82 % and 9.86 % at full load condition because these fuel samples contain less carbon components, also causing CO to burn and convert to CO_2 more thoroughly[18].

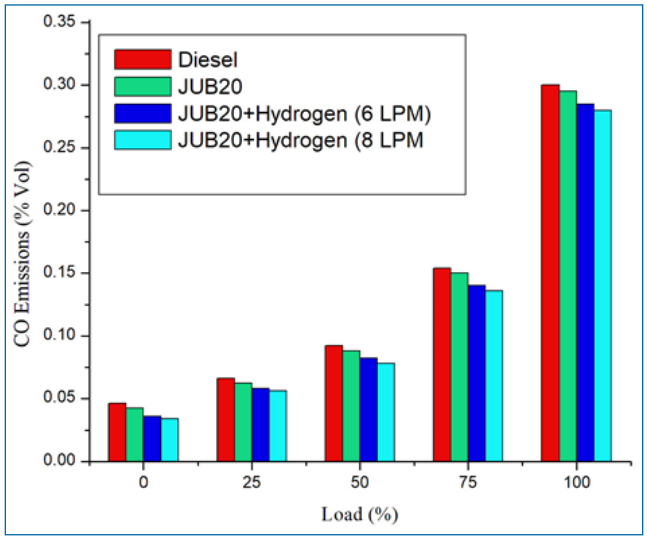


Figure 5. Variation of CO emissions with load.

4.2.3 HC Emissions

Figure 7 depicts the variation of HC emissions for the diesel, JUB20 and JUB20 with hydrogen at 6 lpm and 8 lpm at different load conditions. It is concluded that diesel fuel exhibits higher HC emissions than the JUB20 fuel because diesel contains less content of oxygen than biodiesel[19]. It is also due to the lower HC emissions of the biodiesel and blends, which have a longer retention period than diesel because of their higher viscosity[11].

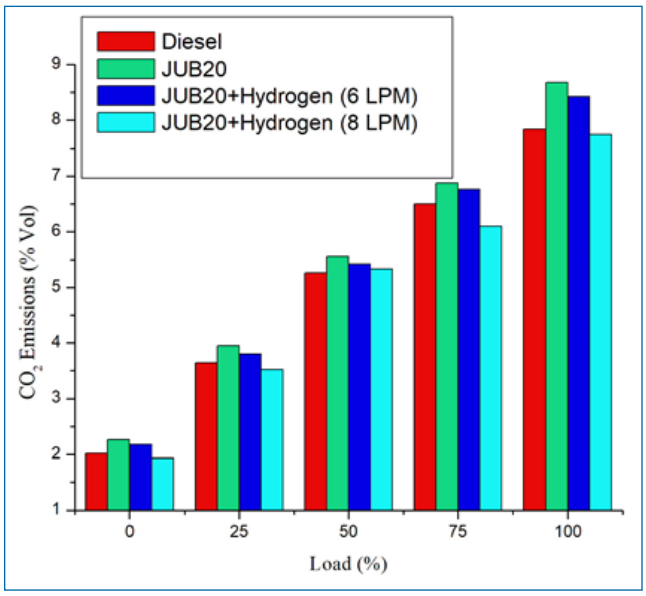


Figure 6. Variation of CO_2 emissions with load.

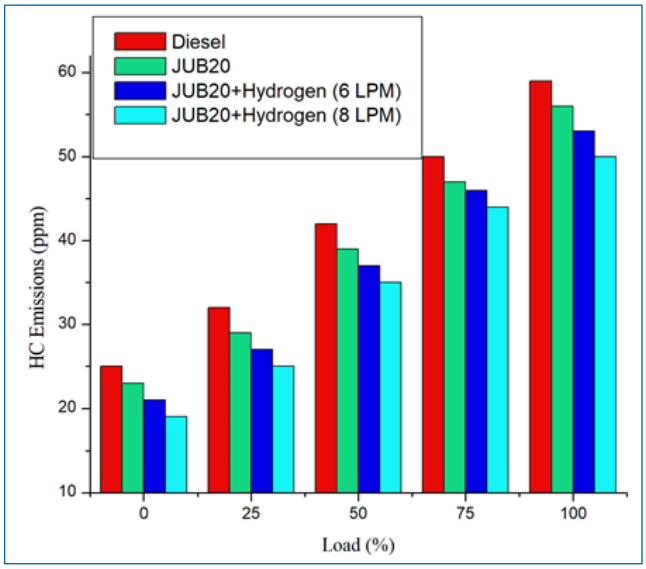


Figure 7. Variation of HC emissions with load.

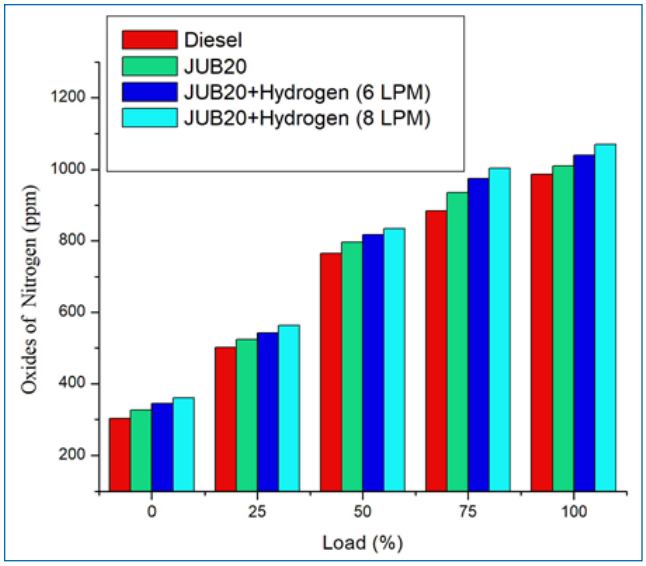


Figure 8. Variation of NO_x emissions with load.

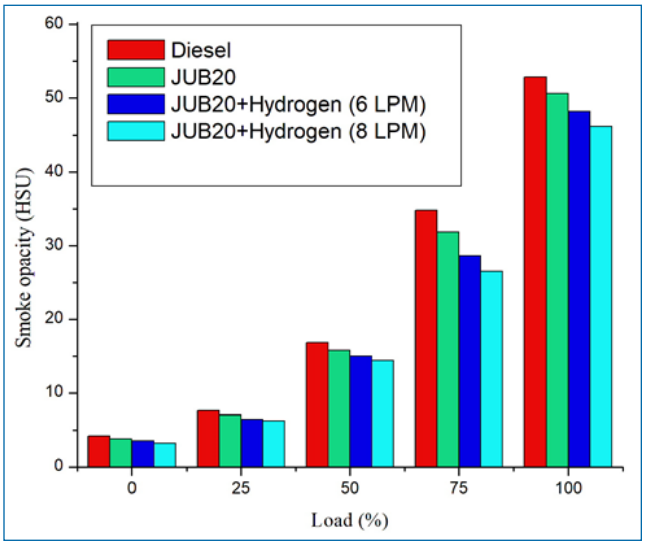


Figure 9. Variation of Smoke Emissions with Load.

The supply of H_2 gas into the engine HC emissions was diminished by 5.42% and 10.71%, respectively, at peak load due to higher atomisation and complete burning of the fuel mixture[5].

4.2.4 NOx Emissions

Figure 8 depicts the variation of oxides of nitrogen for the diesel, JUB20 and JUB20 with hydrogen at 6 lpm and 8 lpm at different load conditions. From the results of this study, NO_x emissions for the JUB20 fuel were increased than the diesel due to higher viscosity and after combustion temperature at all loads[20]. However, the addition of H_2 gas also resulted in an enhancement of NO_x emissions for both the fuels (JUB20 with 6 lpm and 8 lpm) because hydrogen (H_2) has a higher calorific value than biodiesel, so that the temperature of the cylinder also rises after combustion[13].

4.2.5 Smoke Opacity

Figure 9 depicts the variation of Smoke opacity for the diesel, JUB20 and JUB20 with hydrogen at 6 lpm and 8 lpm at different load conditions. Because biodiesel has a larger oxygen content than diesel fuel, it has been found that diesel fuel emits more smoke than JUB20 fuel. In comparison to the JUB20 fuel, the hydrogen addition fuel samples have a lower trend of smoke emissions because of their improved fuel-air combination and increased combustion efficiency[8]. Hydrogen burns faster than diesel or biodiesel, promoting more complete combustion of the fuel-air mixture. This leaves fewer unburnt hydrocarbons and soot particles, which are major contributors to smoke.

5.0 Conclusions

The present study evaluates the engine parameters using diesel, JUB20 biodiesel blend and JUB20 fuel with hydrogen 6 lpm and 8 lpm fuels in a dual fuel engine. Hydrogen induction into JUB20 fuel at 6 lpm and 8 lpm increases the BTE by 4.57% and 8.43%, respectively. Brake specific fuel consumption for the JUB20+ hydrogen 6 lpm and JUB20+hydrogen 8 lpm reduces by 3.8%, 7.8%, respectively. The exhaust emissions, such as CO emissions showed a declining trend of 3.6% and 5.28%, CO_2 emissions by 3.82% and 9.86% at full load condition and HC emissions by 5.42% and 10.71% with the addition of 6 and 8 l/min hydrogen compared to JUB20 fuel. But the NOx emissions were slightly improved over JUB20 fuel with and without the addition of hydrogen. Overall, the study highlights the technical viability of *Juliflora* biodiesel and hydrogen as a dual-fuel solution, offering a sustainable pathway to utilize invasive biomass resources while moving toward low-carbon transportation.

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