Pioneering Green Dual-Fuel Solutions: An Experimental Study on Optimizing CRDI Engine Performance and Emissions with Hydrogen and Oxygenated Fuels

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Abstract. Hydrogen enrichment significantly impacts the performance and emissions of a Common Rail Direct Injection (CRDI) diesel engine using a diesel-Pongamia Pinnata biodiesel blend (B20). Hydrogen, introduced at flow rates of 7 lpm, 10 lpm, and varying load conditions (60%, 80%, and 100%), enhances engine efficiency due to its high calorific value. It reduces harmful emissions like CO and HC while improving brake thermal efficiency (BTE) and brake-specific energy consumption (BSEC). At 80% load, the B20+7H_2 blend achieves an18.52% reduction in BSEC, along with lower emissions of HC and CO by 32.28 and 27.2%, respectively. These results demonstrate hydrogen's potential for cleaner, efficient diesel engine operation.

Keywords: Green Hydrogen, Emission, Performance, CRDI

Introduction

Hydrogen enrichment in internal combustion (IC) engines, particularly diesel engines, has gained attention for improving performance and reducing emissions. Diesel engines, known for their efficiency and versatility, traditionally rely on petroleum-based fuels, raising concerns about greenhouse gas (GHG) emissions and energy sustainability [1-3]. Alternative fuels like biodiesel, hydrogen, and compressed natural gas (CNG) offer cleaner combustion solutions. Hydrogen, with its high combustion temperature, zero carbon emissions, and abundance, stands out as a promising alternative [4-5]. However, challenges such as complex extraction methods, storage risks, and transportation limitations hinder its widespread adoption. Studies reveal hydrogen enrichment enhances combustion efficiency and reduces CO, HC, and soot emissions. Research shows improved Brake Thermal Efficiency (BTE) and reduced emissions with optimal hydrogen induction, but increased NOx emissions at higher loads remain challenging [2-6]. Advanced experimental and numerical investigations highlight hydrogen's potential to improve IC engine performance, making it a viable green fuel alternative.

This review highlights the potential of hydrogen-enriched biodiesel to improve diesel engine performance and reduce emissions [7-9]. Biodiesel, with high oxygen content and low greenhouse gas emissions, is a promising alternative to petroleum fuels, though challenges like higher viscosity and lower calorific value impact its efficiency. Studies show that hydrogen-enriched blends enhance Brake Thermal Efficiency (BTE), reduce Brake Specific Fuel Consumption (BSFC), and significantly lower emissions of hydrocarbons (HC), carbon monoxide (CO), and smoke. Optimal hydrogen flow rates, exhaust gas recirculation (EGR), and biodiesel sources such as rice bran, Pongamia Pinnata, and microalgae further improve performance [10-14]. While hydrogen raises nitrogen oxide (NOx) emissions due to higher combustion temperatures, strategies like EGR and additives mitigate these effects. Palm biodiesel blends with hydrogen or hydroxyl compounds show enhanced thermal efficiency but increased Nox [11-13]. Antioxidants improve biodiesel's stability, albeit with trade-offs in power and fuel consumption. Overall, hydrogen enrichment offers cleaner and more efficient engine performance [14, 15].This study evaluates hydrogen enrichment's impact on high-pressure CRDI engine performance using diesel and B20 biodiesel. At 1500 rpm with different loads hydrogen was inducted at 7 and 10 LPM. Improved fuel atomization enhanced efficiency, addressing gaps in earlier low-pressure engine studies with biodiesel-hydrogen blends.

Experimental setup and procedure

An advanced CRDI engine operating at 1500 rpm and 3.5 kW is studied, with an experimental setup shown in Fig. 1. Key components include injectors, sensors, and an ECU. Cylinder pressure and combustion parameters are monitored using piezoelectric transducers and a data acquisition system. Emissions (CO, HC, NOx) are analyzed via an AVL five-gas analyzer, with specifications in Table 1.

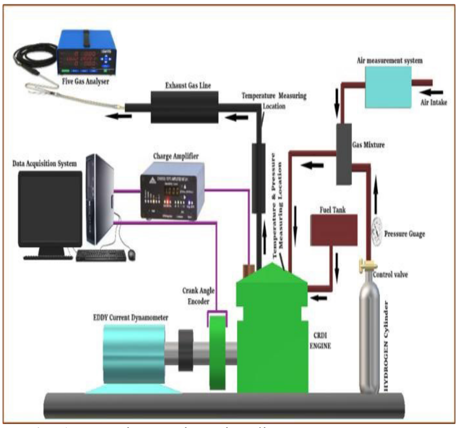

Fig. 1. Experimentation Line diagram

Table 1. Test setup Specifications

Particulars	Specifications
Product	VCR (CRDI), Kirloskar, Water coole
Bore & Stroke	(87.5,110) mm, Eddy current Dynamometer
Type of Engine	One cylinder, Four stroke, 3.5 kw, 1500 rpm
Injection pressure (Max)	600 bar

This study evaluates Pongamia Pinnata biodiesel (B20) for its abundance and potential in CRDI engines. Table 2 presents test fuel characteristics. Experiments at 1500 rpm with 60 bar injection pressure and 230° BTDC timing analyze diesel, B20, and hydrogen blends with 7 LPM and 10 LPM under varying loads, calculating energy share using a defined equation 1. Performance variables are recorded via "Engine soft" software, with mean values calculated from three readings; Table 3 shows precision.

Energy share rate **D** = $$\frac{m_{\text{hydrogen}}\,LHV_{\text{hydrogen}}}{m_{\text{hydrogen}}\,LHV_{\text{hydrogen}} + m_{\text{fuel}}\,LHV_{\text{fuel}}}$$

Table 2. Strategic fuel Properties

Fuel property	D100	B100	B20	H2
Cetanenumber	47	53	52	4-11/ 130 oc
Density(kg/m^3)	831	898	857	0.0834
Viscosity	2.089	5.21	3.3	0.0084
CV(MJ/Kg)	43.5	39.5	42.75	119.93

Table 3. Uncertainty analysis [6]

Instrument	Measurement	Uncertainty
CO(%)	0-10	0.2%
NOx(PPM)	0-5000	0.2%
Speed(RPM)	0-2000	0.2%
HC(PPM)	0-20000	0.2%

Engine Output Parameters

Pressure vs Crank angle

Fig. 2 illustrates crank angle vs. cylinder pressure at low to maximum loading conditions. At 10 LPM hydrogen concentration, in-cylinder pressure drops due to increased oxygen utilization by hydrogen [4-7]. At 100% load, D+7 H_2 reaches a peak pressure of 76.36 bar, 17.85% higher than diesel, while B20+7 H_2 and B20+10 H_2 peak at 76.44 bar and 75.79 bar, exceeding diesel by 18.57% and17.57%, respectively. Hydrogen's high calorific value enhances premixed combustion, increasing pressure, temperature, and turbulence, resulting in superior homogeneity and combustion efficiency [12-15].

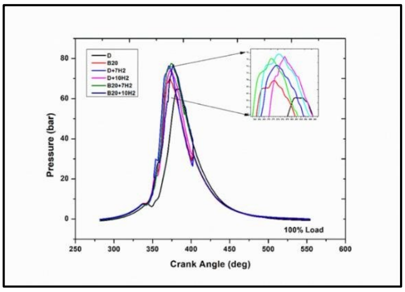

Fig.2. Cylinder pressure vs Crank angle

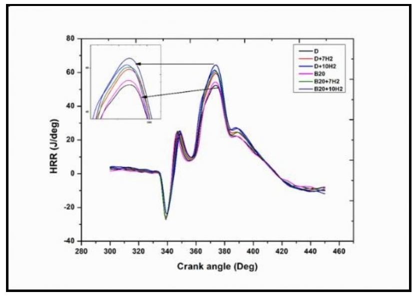

Fig.3. HRR vs Crank angle

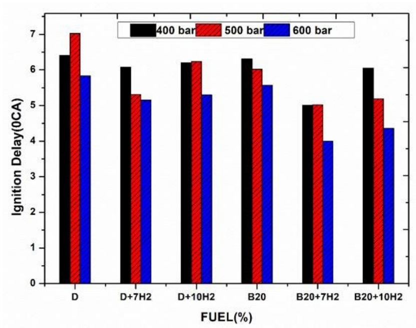

Fig.4. Ignition delay

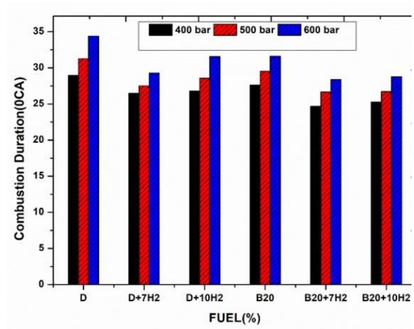

Fig.5. Combustion duration

HRR vs Crank angle

Fig.3 illustrates the relationship between heat release rate (HRR) and crank angle (CA) for D, D+7H2, and B20+10H2 at full load. B20 achieves a maximum HRR of 70.7 J/CA, 24.74% lower than diesel, due to its high LHE and low viscosity. At maximum load, higher in-cylinder temperatures enhance droplet breakup, increasing combustion uniformity. Fuel burnt during the premixed phase significantly affects peak HRR and cylinder pressure [9-11].

Ignition delay (ID)

It measures the time between fuel injection and combustion onset. Figure 4 illustrates ID vs. Load for Test Fuels. Under heavy load, higher in-cylinder temperatures reduce ID [7, 12-14]. B20 shows inconsistent ID due to its high oxygen content and poor mixing, with a 7.68% lower ID than diesel at full load. Hydrogen enrichment increases ID due to its higher auto-ignition temperature. *ID for B20+10H_2 is 24.19% lower than D100 at full load.

Combustion duration (CD)

The period between the start and end of combustion is influenced by fuel type and engine load, as shown in Fig. 5, B20 exhibits higher CD due to low latent heat of evaporation (LHE), but hydrogen enrichment improves CD by enhancing premixed combustion [1,5-9]. At full load, B20+7H2 achieve a CD of 26.370CA, comparable to diesel, while B20+10H2 shows a 17.37% CD lower than diesel, enhancing combustion efficiency.

Brake Specific Energy Consumption (BSEC)

It measures the energy needed to produce one watt of brake power, indicating fuel efficiency. Figure 6 illustrates BSEC at 60% to 100% load for different fuel sets. BSEC decreases with an increasing load, peaking at 80%. At 60% and 80% load, B20's BSEC is 9.0% and 7.6% lower than diesel due to its higher LHV and efficient combustion. Diesel with 7

LPM H2 (D+7H2) achieves 18.52% lower BSEC than pure diesel at 80% load. Hydrogen-enriched fuels, such as B20+7H2 and B20+10H2, initially increase BSEC but reduce it with further hydrogen enrichment, thanks to hydrogen's higher heating value, faster combustion, and efficient energy utilization [7-11].

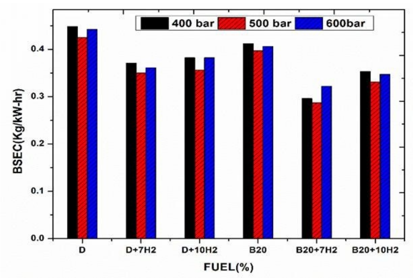

Fig.6. Brake specific energy consumptions

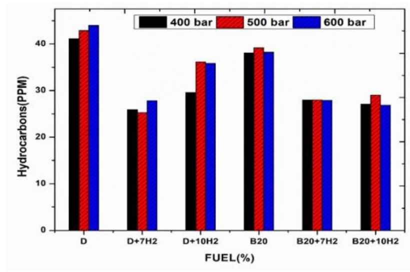

Fig.7. Unburned hydrocarbons

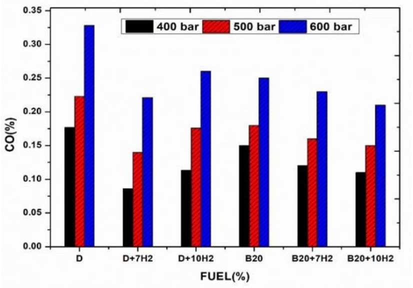

Fig.8. Carbon monoxide

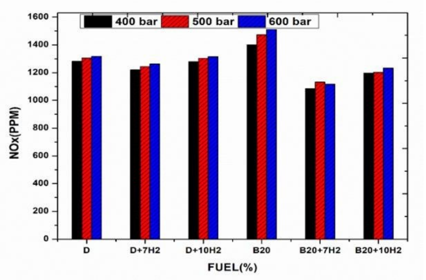

Fig.9. Nitrogen oxide

Hydrocarbon (HC)

The emissions arise from incomplete combustion, increasing with engine load as fuel accumulates in the cylinder. As shown in Fig. 7, B20+7H2reduces HC emissions by 32%, 34.6%, and 36.5% at 60%, 80%, and 100% load, respectively, compared to diesel. Similarly, B20+10H2achieves reductions of 34.16%, 32.28%, and 38.9%, aided by hydrogen's carbon-free structure and complete combustion properties [12-14].

Carbon monoxide (CO)

Fig. 8 illustrates CO emissions for tested fuels under varying loads. B20 shows 12.7%, 19.19%, and 22.8% CO emissions lower than diesel at 60%, 80%, and 100% load due to its oxygen- rich properties promoting complete combustion [6, 9]. Hydrogen enrichment further reduces CO emissions at 7 LPM, with B20+7H2 achieving 29.4%, 27.2%, and 28.1% reductions.

NOx (Nitrogen oxides)

High temperatures cause nitrogen and oxygen to form NOx (Fig.9). NOx emissions increase with higher cylinder temperatures caused by higher loads. B20 Pongamia Pinnata biodiesel blend emits 8.3%, 13.2%, and 13.5% more NOx than diesel at 60%, 80%, and 100% loads due to its oxygen-rich structure [2, 3, 7-11]. B20 +7H2 and B20+10H2 show NOx emissions of 6.7% and 5.2% higher than diesel, respectively.

Conclusion

This study highlights the comparative performance of different hydrogen enrichment strategies in a CRDI engine fueled with biodiesel-diesel blends. Notably, the B20+7H2 blend demonstrated superior performance across multiple parameters. Hydrogen enrichment led to enhanced in-cylinder pressure and heat release rate (HRR), with B20+7H2 achieving improvements of 18.3% and 18.78%, respectively, at 80% engine load. The blend also recorded a Brake

Thermal Efficiency (BTE) of 29.69% and a reduced Brake Specific Energy Consumption (BSEC) of 0.287 kg/kWh. Furthermore, emissions of hydrocarbons (HC) and carbon monoxide (CO) were reduced by 34.6% and 27.2%, respectively. Although NOx emissions tend to rise due to higher combustion temperatures, the B20+7H2 blend showed a 13.2% reduction in NOx compared to diesel under high-load conditions. The use of B20 alone resulted in extended combustion duration (CD) and ignition delay (ID), while hydrogen enrichment significantly reduced CD by 14.6% in B20+7H2 at 80% load. These findings suggest that controlled hydrogen supplementation in biodiesel-diesel blends can be a promising pathway for achieving cleaner and more efficient combustion. The practical implications are substantial for sectors such as transportation and stationary power generation, particularly in regions prioritizing decarbonization. Future work should investigate the long-term durability of engine components under hydrogen-rich operation and assess economic feasibility at scale to facilitate real-world adoption.

Nomenclature

D	Diesel
lpm	Liter per minute
D+7H_2	Diesel+7 lpm (H_2)
D+10H_2	Diesel+10 lpm (H_2)
B20	20% Biodiesel +80% diesel
B20+7H_2	B20+7 lpm (H_2)
B20+10H_2	B20+10 lpm (H_2)
HRR	Heat release rate
NOx	Nitrogen-oxides

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