Fuel 389 (2025) 134592

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Effects of fuel injection pressure on the double-cylinder dual fuel turbocharged CRDI engine characteristics with H_2 enrichment

Neetesh Kumar Gupta *, Tikendra Nath Verma *

Department of Mechanical Engineering, Maulana Azad National Institute of Technology Bhopal 462003 India

A R T I C L E I N F O

Keywords:
Hydrogen Share
Turbocharged
Injection pressure
Performance
Combustion

A B S T R A C T

This study examined the engine's performance, combustion, and emission characteristics utilizing a double-cylinder boosted common rail direct injection CI engine running on a bi-fuel system with hydrogen enrichment as a backup fuel and neat diesel as the primary fuel. The working conditions were kept at 2000 rpm, with 16.5 CR and 15 ^{o}bTDC FIT, while variable FIPs (500, 550, 600 bar), variable loading conditions (12.5, 25, 37.5, and 50 Nm) and variable fuel blends of hydrogen (H20%, H35% and H50%) with neat diesel fuel were chosen for the study. The test results indicated the effect of rising injection pressure at full load (50 Nm) along with D + H50% fuel composition for optimal performance (600 bar). Under optimum conditions, BTE has reached a maximum of 33.98 %, and BSFC has the highest decrement of 240.91 g/kWh than neat diesel. The variables namely in-cylinder pressure, HRR, HES, and EGT recorded maximum values of 76.61 bar, 103.16 J/^{o}CA, 25.67 %, and 560.76 °C under D + H50% fuel blend conditions with a corresponding improvement in NO_x (70.17 %) and lowering in smoke emissions (55.13 %). In particular, 50 % hydrogen concentration with diesel (D + H50%) displayed better performance and emission characteristics than other gasoline mixes, but with a slight increase in NOx emissions. This study concluded contribution of hydrogen energy in developing cleaner CI engine technologies along with a successful transition towards sustainable fuel alternatives.

1. Introduction

Internal combustion engines (ICE) are differentiated through the fuel combustion approach, which corresponds to spark ignition (SI) and compression ignition (CI). Normally, in SI engines, spark plugs are utilized in the engine cylinders for the combustion triggering of gasoline introduced through a carburetor [1]. On the other hand, the high compression ratio design and use of diesel fuel in CI engines enable auto-ignition of the fuel during the compression stroke[2]. An amount of diesel is injected directly into the combustion chamber, which when compressed attains sufficient ignition energy and combusts. One of the benefits of CI engines over SI ones is that they offer higher achievable thermal efficiency as it is operated at a higher compression ratio [3]. In addition, larger torque and power output are generally expected for diesel engines compared to gasoline. However, higher harmful NOx and particulate matter emissions are usually found in CI engines as compared with SI engines due to the higher carbon content of the diesel fuel used[4]. Although fossil fuel is finite and limited, the demand for non-renewable fossil oils is still growing every day due to heavy reliance on them from human daily activities including electricity generation, transportation, industries, and more [5]. The world energy crisis has put us in danger of running out of subterranean carbon reserves, experiencing economic instability, and experiencing environmental disasters [6,7]. Global warming, caused by rising temperatures or emissions from fossil fuels used in transportation and manufacturing, is a major issue that affects the entire world[8]. The concept of using hydrogen as an ICE fuel may be traced back to the 1970 s since it is recognized as one of the most promising solutions as a clean burning fuel. Hydrogen is identified as the most abundant element on Earth and even in outer space. Besides, hydrogen as a gaseous fuel exhibits several advantages over liquid gasoline and diesel in terms of engine cold start, generally fewer pollutant emissions, and lubricating oil contamination [9]. Hydrogen as a non-toxic and carbon-free gas does not contribute to emissions of unburned hydrocarbon (UBHC) and carbon oxides, thus ensuring great reductions in pollution from ICEs[10]. India can achieve its goals of growing its hydrogen production because of its abundant renewable energy potential, but it has to quickly boost capacity [11]. Worldwide initiatives to lessen climatic variation are aimed at dropping GHG emissions and shifting to more renewable resources, as the world confronts an urgent decarbonization issue [12,13]. **Supplementary Fig. 1**. shows how several industries, such as manufacturing, transportation,

* Corresponding authors.
E-mail addresses: ntshgupta657@gmail.com (N.K. Gupta), verma.tikks@manit.ac.in (T.N. Verma).

https://doi.org/10.1016/j.fuel.2025.134592
Received 2 September 2024; Received in revised form 15 January 2025; Accepted 3 February 2025
Available online 8 February 2025

Nomenclature Units

H_2	Hydrogen
D	Neat Diesel
UBHC	Unburned Hydro Carbon
CO	Carbon Monoxide
BTE	Brake Thermal Efficiency
NOx	Oxides of Nitrogen
BP	Brake Power
HES	Hydrogen Energy Share
CO_2	Carbon Dioxide
CI	Compression Ignition
EGT	Exhaust Gas Temperature
C.R.	Compression Ratio
HRR	Heat Release Rate
EGR	Exhaust Gas Recirculation
NZE	Net Zero Emission
ECU	Electronic Circuit Unit
PFI	Port Fuel Injection
FIP	Fuel Injection Pressure
FIT	Fuel Injection Timing
H20%	(20 %) Valve Opening of Hydrogen Gas Injector
H35%	(35 %) Valve Opening of Hydrogen Gas Injector
H50%	(50 %) Valve Opening of Hydrogen Gas Injector
^{o}bTDC	Degree Before Top Dead Centre
CAGR	Compound Annual Growth Rate
BEMP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CRDI	Common Rail Direct Injection
Lpm	Liter Per Minute
Rpm	Rotation Per Minute
CC	Cubic Centimeter
PPM	Parts-Per Million
BSN	Bosch Smoke Number
^{o}CA	Degree Crank Angle
^{o}C	Degree Celsius
BHP	Brake Horse Power
Mt	Metric Tons
GW	Gigawatt
Psi	Pound Square Inch
MMTPA	Millon Metric Tons Per Annum
K	Kelvin

Abbreviation

Q_{net}	Total heat release rate (HRR) in J/°CA
ϒ	Ratio of specific heats, $C_p/(C_p - R)$
R	Gas constant in J/kmol-K
C_p	Specific heat at constant pressure in J/kmol-K
V	Instantaneous volume of the cylinder in m^3
P	Cylinder pressure in bar

and power generation, depend on hydrogen to operate with less emissions [14]. With its wide availability and high energy density, H_2 is likeliest neat energy source for the future. At 119.53 MJ/kg, H_2 heats 3.5–4 times faster than hydrocarbon fuels like gasoline, coke, etc. [15,16]. To cut down on emissions from internal combustion engines, hydrogen injection diesel engine systems add hydrogen, which is created on demand from pure deionized water to diesel engines[17]. The quantity of H_2 used globally in 2022 was 95 Mt, up almost 3 % from our updated estimate for 2021[18]. This continued the upward trend that was only halted in 2022 because of the COVID-19 epidemic and the global economic slowdown[19]. **Supplementary Fig. 2**. depicts the historical, sector-by-sector, and 2020–2030 hydrogen utilization in the Net Zero Emission by 2050 scenario[20]. The use of hydrogen has increased by 6 % yearly through the end of this decade[21], The latest iteration by 2050 the total zero emissions plan states[22]. This suggests using more than 150 Mt of hydrogen by 2030, of which new uses will account for roughly 40 % [23]. At COP 26, the nation established a higher target of 500 GW of energy derived from non-fossil fuels by 2030. In 2023, it achieved 175 GW of reusable energy, surpassing the capacity of 190.57 GW as of March 2024 as shown in **Supplementary Fig. 3** [24]. India also committed to achieving Net Zero by 2070 and energy independence by 2047 during this session [25]. By 2070 acknowledging the potential of clean hydrogen to attain zero emission, India initiated The National Green Hydrogen Mission (NGHM) in 2023 [26]. Energy-exergy analysis is an important assessment mechanism that identifies energy utilization and its losses. The literature lists several studies on biodiesel-based energy-exergy analysis. Tiwari et al. utilized diverse combinations of spirulina microalgae diesel and biodiesel (volumetric basis) in a cylinder CI engine. Energy-exergy and sustainability studies suggested that a 20 % blend of microalgae showed comparable results to that of diesel[27]. The possibility of a 20 % blend was proposed by Tiwari et al.'s other work by optimization of diesel emissions and performance characteristics utilizing neat diesel mixes with microalgae biodiesel, load, and compression ratio by RSM was adopted for maximization of input variables[28,29]. Some researchers investigated other alternatives apart from biodiesel as a possible fuel for diesel-powered machinery such as fuel additives like dimethoxymethane. K. Bayramoğlu et al. utilized dimethoxymethane with neat diesel (volumetric basis) to improve engine performance and lower engine exhaust emissions. The results illustrated that 20 % dimethoxymethane produced improved engine performance with minimization in engine emissions such as CO, HC, and smoke with a little penalty in NO_x emissions owing to elevated cylinder temperatures[30]. The exhaust emissions have also shown a diminishing trend owing to clean burning nature and hydrogen's carbonless form with a slight penalty in NO_x emissions due to improved cylinder temperature inside engine cylinde [31]. Wang, Hechun, et al and Fakhari, Amir Hossein, et alstudied three different hydrogen enrichment percentages (2.5 %, 5 %, and 7.5 %) to turbocharged 4-cylinder CI engine's standard diesel operated at variable speeds (1000–2500 min^{-1}). At 7.5 % hydrogen addition, brake torque was improved by 8.3 % (speed 1250 min^{-1}), and brake power was improved by 17 % (speed 2250 min^{-1}). The emissions of smoke were also reduced greatly with addition of hydrogen to diesel with a little penalty in NO_x emissions [1,32]. Similarly, Cernat et al., and Kumar et al., also studied results of variable H_2 enrichments on dual-fuel diesel engines. Specifications like braking force, thermal efficiency, and in-cylinder pressure have shown considerable better while consumption of specific fuel, ignition delay, and emissions like HC, CO_2 and CO have shown diminishing trends. In all the studies, NO_x emissions have shown better due to elevated temperatures in the cylinder [33,34]. Saravanan, N. et al. and Tsujimura et al. performed tests on direct injection Dual fuel operation for diesel engines using variable hydrogen induction through the port injection method. During the study, it was found that 30° CA, 7.5 LPM, and Injection time, duration, and flow rate were shown to be optimal at 5°bTDC gas exchange. The BTE and NO_x emissions indicated an improvement of 17 % and 75 % while smoke emissions were reduced by 44 % than neat diesel because H_2 may burn at greater temperatures. At higher loads engines and higher flow rates of hydrogen, a knocking phenomenon was observed. To limit the NO_x emissions produced after introduction of H_2 as a dual fuel in diesel engines, the exhaust gas recirculation method was adopted which lessens the NO_x emissions produced after combustion owing to lowering of peak combustion temperatures [35,36]. Nag et al., Dahake, and Malkhede utilized EGR methods to minimize the NO_x produced post-combustion of hydrogen in diesel engines. That was noted NO_x was lowered besides a decrement in brake thermal efficiency while other emissions like smoke, CO, HC, and CO_2, were improved due to the unavailability of oxygen which limits combustion operation[37,38]. Rajak et al. performed experimental and numerical investigation of diethyl ether, n-butanol, and hydrogen enrichment to baseline diesel fuel in dual-fuel diesel engines at different compression ratios (19.5 CR). The outcomes of the study revealed that peak cylinder pressures were observed at high compression ratios, BSFC was reduced with hydrogen addition while NO_x emissions were significantly enhanced by adding H_2 [39]. Verma et al. researched paired fuel 4.4 kW Kirloskar CI engine employing diesel in diesel fuel mode and biogas, CNG, and H_2 as the alternate fuels, all while keeping at 20, 23, 26, 29, and 32 °bTDC timing of injection. The outcomes of the trial revealed that as injection time improved, the dual fuel mode's emissions for H_2 and diesel, including HC, CO, and smoke, dropped at high load but NOx significantly rose[40,41]. Singh et al. studied clean diesel and H_2 enrichment of (10–40 %) with a gap of 10 % respectively, at 2200 rpm of constant speed, and loads form of BMEP values of 1.38, 3.47, and 5.66 bar. The results demonstrated that when turbocharging the highest known thermal efficiency indicated better at D + H2 (40 %), at 5.6 bar BEMP was observed 49.6 % than diesel (39.4 %), however, the greatest rise in volumetric efficiency was seen 95.8 % than diesel (87.6 %) at 5.6 bar, by a 20.1 kPa boost pressure surge respectively. The emissions such as nitrogen oxides were improved and reduction in smoke opacity with 40 % hydrogen induction [42]. Gürbüz and Akçay invested in the impacts of an external supercharger on the fuel economy, emissions, performance, and ecological-social cost signals of an H_2-fueled spark ignition engine running at 1600 rpm in a lean mixture at boosting pressures of 10, 20, 30, and 40-kilo pascals. In contrast to when air is normally aspirated and ignition is timed perfectly. The intake manifold was filled with H_2 at various bars, the results were a rise in NO_x emissions of 45.2 %, a rise in IMEP and thermal efficiency of 14.2 % and 38.9 % with an elevating pressure of 40 kPa, as well as an increase in its ecological and social price of 21.7 %. However, the cost and specific fuel use declined by almost 18.4 %. [3,43]. A critical literature review was carried out on the specific work, the effect of H2 enrichment with the variation of fuel injection pressure performed by the various researchers in recent years compared to present experimental work, shown in Table 1 which is given below.

Several studies in the literature discuss how adding H_2 to diesel engines at varying flow rates and fuel injection pressure affects the engine's performance, emissions, and combustion in a single-cylinder diesel engine. Based on a review of the literature, it can be inferred that not much research has been done on how fuel injection pressure and H_2 enrichment affect multiple-cylinder engine performance, combustion, and emissions. Therefore, the current study examines how fuel injection pressure and H_2 enrichment affect turbo double-cylinder diesel engines' combustion and emission characteristics as well as their overall performance. Majority of the studies are focused on single-cylinder naturally aspirated engines. The present work is an attempt to determine the optimum injection pressure out of 3 pressures on a twin-cylinder turbocharged CRDi engine using H_2 enrichment.

2. Materials and methods

2.1. Experimental setup and process

The test engine is a four-stroke, computerized, double-cylinder, turbocharged, cooled-water, directly induced diesel engine with a maximum power of 33.5 kW and a compression ratio of 16.5. Fig. 1. illustrates the representation of the tests performed setup used in the study. The details of the test engine are provided in Table 2. The tests were conducted at a constant speed of 2000 rpm, under variable load conditions ranging from 12.5 to 50 Nm (12.5 Nm increment between successive loads) applied using a precision dynamometer (water-cooled eddy current).

Table 1
Literature Review.

Author (Reference No.)	Experiment operating conditions	Experiment outcomes
Current Study	Twin cylinder, turbocharged 4-S CRDi diesel engine, Speed Constant of 2000 rpm, Variable loading (12.5, 25, 37.5, and 50 Nm) FIT of 15°CA bTDC,FIPs (500, 550, 600 bar) Opening % of H_2 gas injector valve (20, 35, and 50 %) Hydrogen mass flow rates at H20%, H35%, and H50% are 0.03312 kg/h, 0.05796 kg/h, and 0.08282 kg/h **Test Fuels** Diesel and Hydrogen (D + H20%, D + H35%, and D + H50%)	**At optimum conditions** Under FIP of 600 bar, D + H50%, at full load **Performance Analysis** BTE and BP maximum by 33.98 % and 9.7 kW BSFC minimum 240.91 g/kWh **Combustion Analysis** ICP, HRR, and EGT increased by 12.76 %, 29.9 %, and 39.17 % **Emission Analysis** Smoke decreased by 55.13 % and NOx up by 70.17 % HES Decreases from increasing fuel injection pressure and loads, but it will increase as fraction-wise increases from H20% to H50%
Das, S. et al. [44]	Single-cylinder 4-S diesel engine, Speed (constant) of 1500 rpm, FIPs (240, 420, and 600 bar), FITs (23,25, and 27°CA bTDC), and hydrogen flow rate (7 and 10 lpm) under full load **Test Fuels**Diesel and Hydrogen (7, and 10 lpm)	**At optimum conditions** Under 25°CA bTDC IT, 600 bar FIP, and 10 lpm hydrogen flow rate at full load **Performance Analysis** BTE improved by 31.09 %, and BSFC minimum 0.28Kg/kWh **Combustion Analysis** ICP and HRR improved by 28.04 % and 22.70 %, **Emission Analysis** NOX emission increases by 53.49 %, lower CO (31.25 %) and HC (11.11 %) emissions
Khandal, S.V. et al. [45]	Single-cylinder 4-S diesel engine, Constant speed of 1500 rpm, injection pressures (800–1000 bar), loading conditions BP (1.04, 2.08, 3.12, 4.16, and 5.20 KW) Hydrogen flow rates (0.1, 0.16, 0.22 Kg/h) **Test Fuels** Diesel/Biodiesel and Hydrogen	BTE was higher 11 % lower HC and 15.4 % lower CO, CRDi engine operation in DF mode with H2 yielded higher NOx at higher loads as compared to lower loads under 900 bar IP and 0.22 kg/h flow rate of hydrogen.
Gnanamoorthi, V. et al. [46]	Single-cylinder 4-S diesel engine, Constant speed of 1500 rpm, FIT of 23°CA bTDC, hydrogen flow rates (6–36 lpm with a gap of 6 lpm) Fuel injection pressure of 70 MPA **Test Fuels** Diesel and Hydrogen .	**At optimum condition** (Under Hydrogen flow rate of 30 lpm and FIP of 70 MPa) at full load **Performance Analysis**BTE maximum (30.65 %)BSFC decrease (23.48 %) **Combustion Analysis** HRR and ICP increased by 28.66 %, and 28.9 %. **Emission Analysis** Reduces the harmful emissions like CO, CO2, UHC, and smoke by 22.3 %, 14 %, 32.74 %, and 43.86 %, and NOx increased by 7.3 % compared to that of the diesel fuel

(*continued on next page*)

Table 1 (*continued*)

Author (Reference No.)	Experiment operating conditions	Experiment outcomes
Kanth, S. et al. [6]	Single-cylinder 4-S CRDI diesel engine, Constant speed of 1500 rpm, FIPs (220, 240, 260 bar), FITs (12, 23, 25°CA bTDC), Hydrogen flow rate (7, 10, 13 lpm) **Test Fuels** Diesel, Biodiesel(Karanja) , and Hydrogen	**At optimum condition** (Under KB20H10, 240 bar, 23°CA bTDC) at full load **Performance Analysis** BTE improved by 4 % than diesel **Combustion Analysis** Ignition delay 25 % higher than neat diesel fuel operation. **Emission Analysis** Smoke Opacity and CO were reduced by 28.7 % and 16 % than diesel An increase in the injection pressure and timing lowers HES.
Kumar, M. et al. [47]	Single-cylinder 4-S CRDI diesel engine, Constant speed of 1500 rpm, FIPs (500, 1000, 1500 bar), FITs (5, 11, 17°CA bTDC), Hydrogen flow rate (5, 7, 9 lpm) **Test Fuels**Diesel, Biodiesel (Jatropha) , and Hydrogen	**At optimum conditions** Under Hydrogen biodiesel blend (H-9lpm, 1500 bar, 17 °CA bTDC) at full load **Performance Analysis** BTE maximum 32.15 % **Combustion Analysis** ICP & HRR 72.09 bar, 66.07 J/^{o}C **Emission Analysis** UHC and soot emissions were reduced by 59.52 % and 46.15 %, and NOx increased by 20.61 % respectively.
Kanth, S., Ananad, t. et al. [48]	Single-cylinder 4-S CRDi diesel engines FIP (220, 240, 260 bar), FIT (20, 22, 24, 26°CA bTDC), Hydrogen flow rate (constant) 7lpm **Test Fuels**Diesel, Biodiesel (Rice bran (RB) 10 % and 20 %) and Hydrogen	**At optimum conditions** Under RB10 + H_2, 240 bar, 24°CA bTDC at full load **Performance Analysis** BTE increase by 3.32 % compared to diesel fuel **Combustion Analysis** ICP Maximum 68.7 bar, HRR of 52 J/^{o}CA **Emission Analysis** Reduction in CO, HC, and smoke opacity emission by 17 %, 22 %, and 16 %, and NOx 12 % increase respectively
Köse, H. et al. [49]	Four-cylinder 4-S CRDi diesel engine, Variable speeds (1000–2500 rpm a gap of 250), Hydrogen rates (2.5 5, 7.5 %), injection pressure 230 bar **Test Fuels** Diesel and Hydrogen	**At optimum conditions** Under H7.5 % and 2250 rpm at full load **Performance Analysis** Power max. 65.63 kW, Volumetric efficiency increased 13 % BTE increased by 10.8 % **Combustion Analysis** EGT increased 9.4 % (449 °C) **Emission Analysis** $CO_{2,}$ HC decreases by 8.4 %, 28 %, and NOx increased by 17.8 %
Saravanan, B. et al. [50]	Single cylinder 4-S CRDi diesel engine, Speed (1500 rpm), FIPs (200, 260 bar) and FITs (23, 27^{o}bTDC), Hydrogen(H2) rate (10 lpm), different load of 4 kg (25 %), 8.1 kg (50 %), 12.1 kg(75 %), and 16.2 kg (100 %)	**At optimum conditions** Under FIP of 260 bar and 27^{o}bTDC with H2 (10 lpm) full load **Performance Analysis** BTE increased by 10 %, BSFC reduced by 9 % whilereducing brake-specific fuel consumption (9 %) and.
	Test Fuels Diesel/Biodiesel, HydrogenPure diesel (B0), Biodiesel (B20) , and H2 + B20 fuel blends	**Combustion Analysis** ICP and HRR risen by 5 %, and 7.4 %. Ignition delay (ID) was decreased by maximum of 7.6 % with H2 enriched B20 than diesel **Emission Analysis**Less emissions such as HC (16 %), carbon monoxide (12 %), and smoke (18 %) than diesel, except NOx (increases

A rotary encoder (Autonics E5058) was used for crank angle measurement, the fuel measurement was done using a solenoid valve. T-MAF sensor was used to calculate the airflow measurement in kg/hr. The performance and combustion characteristics of the test engine were studied using Engine Scan and NIRA Open ECU software which measures the engine speed, cylinder pressure, cylinder temperature, mass flow rate of air, mass flow rate of coolant, temperature of coolant, and mass flow rate of hydrogen. The intake manifold allowed air and hydrogen gas into the cylinder using a solenoid injector. The hydrogen and air mixture were made uniformly by using a mixing chamber. The pressure of hydrogen stored in high pressure cylinder was lowered from 200 bar to 2 bar using a pressure regulator. AVL smoke meter and Testo 350 gas analyzer were used to measure the emissions of NOx and smoke opacity, respectively. The experiments were performed at ambient conditions i.e. 25℃ (298.15 K) and 100 kPa pressure. The experimental conditions were kept as 15°bTDC diesel fuel injection timing while three diesel fuel injection pressures 500, 550 and 600 bar were chosen for this study. Initially, the engine was made to run idly under no-load conditions for 10 – 15 min. The mass flow rates of hydrogen share (H20%, H35%, H50%) were 0.03312 kg/h, 0.05796 kg/h, and 0.08282 kg/h respectively. D + H20% indicates a 20 % opening of the hydrogen gas injector's valve along with the atmospheric air and accordingly diesel taken from the fuel tank as per requirement. For a particular experiment, only diesel consumption varies due to changes in loading conditions. Hydrogen quantity is fixed from the hydrogen gas cylinder to the engine combustion chamber.

Table 3**.** shows a comparison of different physicochemical characteristics of the test fuels utilized in this investigation, such as hydrogen and plain diesel [51].

The experimental test matrix is represented in Table 4. The schematic experimental setup is illustrated in Fig. 2. In **equation (1)** the measurement of HRR was based on the 1st Rule of thermodynamics specific to corresponding °CA position [52] as follows:

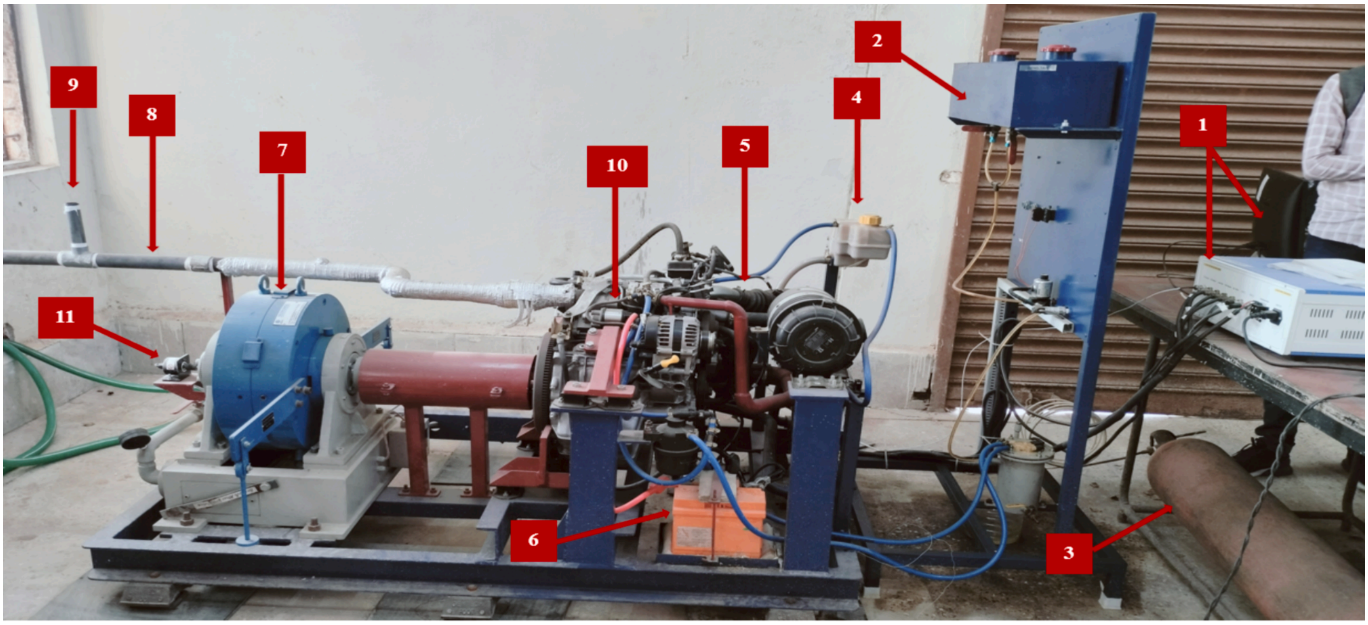
$$Q_{net} = \frac{\gamma}{(\gamma - 1)}[Pdv] + \frac{1}{(\gamma - 1)}[Vdp] \tag{1}$$

where,

Q_{net} = Total heat release rate (HRR) in J/°CA
ϒ = Ratio of specific heats, C_p/ (C_p – R)
R = Gas constant in J/kmol-K
C_p = Specific heat at constant pressure in J/kmol-K
V = Instantaneous volume of the cylinder in m^3
P = Cylinder pressure in bar

3. Uncertainty analysis

The repeatability of experimental observations to ascertain the derived engine performance parameters has been thoroughly examined through a measurement uncertainty analysis, taking into account the



1. **Data Acquisition System (DAS), 2. Dual Fuel Tank, 3. Hydrogen Gas Cylinder, 4. Coolant Box, 5. Twin Cylinder CRDI Engine, 6. Battery, 7. Dynamometer (Eddy Current), 8. Exhaust Pipe Line, 9. Exhaust Gases to Analyzer, 10. Turbocharger, 11. Crank Angle Encoder**

Fig. 1. Experimental test engine setup.

Table 2
Specification of experimental engine.

S. No.	Terms	Technical specification
1	Model	2CD_Supro_V1.0_Base
2	Engine Capacity (cc)	909, and turbocharged engine
3	Bore (mm)	83
4	Stroke Length (mm)	84
5	Max. Power @ RPM	45 HP @ 3750 RPM
6	Max. Torque @ RPM	90 NM @ 1800 RPM
7	Number of Valves/Cylinder	2
8	Connecting Rod Length (Centre to Centre) (mm)	141
9	Engine Oil Specification, Capacity	SAE 15 W40, 3.25 Liters
10	Dynamometer	Eddy Current Dynamometers
11	Nozzle Injector Type: Solenoid	Nozzle Diameter: 145 µm, No. of holes: 6

instrumentation used, its calibration, the accuracy of the observations, and the methods used to conduct the experimentation in a specific setting. With fervor, the root mean square method has been employed to determine the performance parameters for the accrued uncertainty analysis, where net uncertainty ΔU is evaluated percentage of a profusion Q, detachment on the free erratics x_1, x_2, x_3, ………. x_n (i.e., Q = f [x_1, x_2, x_3 ………. x_n]) accepting distinct mistakes Δx_1, Δx_2, Δx_3 [53,54]. The aforementioned has been extensively added to **Supplementary Table 1**. under this hypothesis. The following is how the uncertainty is calculated as follows:

$$\Delta U = \sqrt{\left(\frac{\partial u}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial u}{\partial x_2}\Delta x_2\right)^2 + \left(\frac{\partial u}{\partial x_3}\Delta x_3\right)^2 + \ldots\ldots\ldots\ldots + \left(\frac{\partial u}{\partial x_n}\Delta x_n\right)^2} = \pm 1.97$$

Under uncertainty analysis, the list of observed values (speed, temperature, pressure, NO_x, smoke opacity, load, crank angle encoder, and fuel burette measurement) together with the calculated values are computed

Table 3
Properties of test fuels [51].

Properties of Hydrogen and Diesel fuel			
S. No.	**Property**	**Hydrogen**	**Diesel**
1.	Molecular Weight (g/mol)	2.016	170
2.	Density at 16 °C and 1.01 bar (kg/m^3)	0.0838	833 – 881
3.	Auto-ignition Temp (K)	858	530
4.	Stoichiometric air mass quantity (kg air)	34.32	14.5
5.	Calorific value (MJ/kg)	119.617	41.855
6.	Flame speed (cm/s)	265—325	30
7.	Quenching gap in NTP air (cm)	0.064	–
8.	Cetane No.	0	40–60
9.	Energy density at 15 °C and 100 kPa (MJ/m^3)	10.3	35.8
10.	Boiling Point (K)	20.2	453–653
11.	Specific gravity	0.091	0.83
12.	Cost (Rs.)	300 – 400 per kg	91.84 per litre

Table 4
Experimental test matrix.

Name of Parameter	Values
Load (Nm)	12.5, 25, 37.5, and 50 Nm
Fuel Injection Pressure (FIP) in bar	500, 550, and 600 bar
Speed (rpm), Compression Ratio, and Injection timing	2000 rpm (constant), 16.5 (constant), and 15°bTDC
Test fuels	Diesel (D) and Hydrogen blends (D + H20%, D + H35%, and D + H50%)
Hydrogen mass flow rate from both gas injectors (0.023 g/sec. each)	0.1656 kg/h = 33.658 L per minute (lpm)

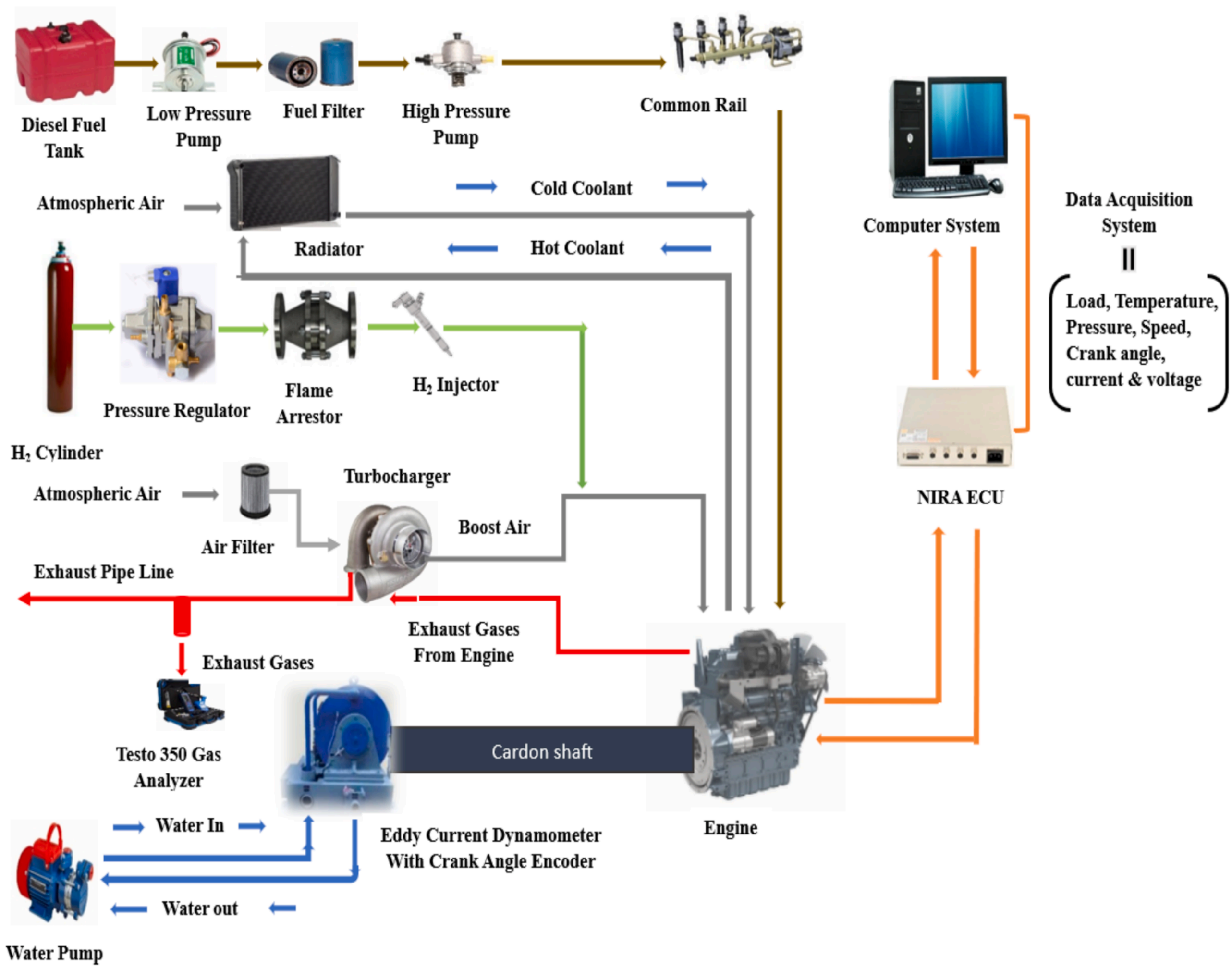


Fig. 2. Detailed Schematic experimental setup.

to determine overall uncertainty in measurement. Supplementary Table 2**.** shows the correctness of the pieces of equipment employed for the performed tests. Therefore, the total percentage (%) of uncertainty is ± 1.97.

4. Result and Discussions

In a hydrogen-enriched (H20% to H50%) engine, the current work aims to determine the ideal fuel injection pressure (diesel–hydrogen share). Engine BTE variation concerning brake power is depicted in Fig. 3**.** BTE increases as hydrogen enrichment increases. As hydrogen enrichment rises to 50 %, Fig. 8**.** illustrate that NOx emissions climb as well, particularly at greater loads. The results are determined based on the changing injection pressure at a D + H50%. The results were obtained based on the engines operating conditions in addition to hydrogen ble of D + H20%, D + H35%, and D + H50% with neat diesel (D) and various loading situations (12.5 Nm, 25 Nm, 37.5 Nm, and 50 Nm), fuel injection pressure (FIP) is 500 bar, 550 bar, and 600 bar.

4.1. Performance analysis

4.1.1. Brake thermal efficiency (BTE)

The relationship between brake power and engine net heat supply is known as brake thermal efficiency. BTE increases with rises in proportion to hydrogen enrichment, because of this enhanced rate of combustion According to Fig. 3**. (a), (b),** and **(c)** at full load (50 Nm) at 500, of FIP, the BTE improves from neat diesel (D) to 50 % of hydrogen concentration with diesel (D + H50%), are (21.09 % to 28.88 %), which is 7.79 % higher than neat diesel. At FIP of 550 bar, BTE rises from 22.32 % (D) to 30.96 % (D + H50%), 8.64 % more from neat diesel. At injection pressure of 600 bar BTE was obtained maximum from 23.55 % (D) to 33.98 % (D + H50%) respectively. The figure shows that the BTE increases of various hydrogen blends, ranging from neat diesel (D) to D + H50%, at a FIP of 600 bar BTE has achieved 10.43 % more than the neat diesel in comparison to 500, and 550 bar injection pressure. Fig. 3**. (a), (b), and (c)** depict, that BTE increases as various injection pressure increases because better combustion, a higher-octane rating, and leaner hydrogen combustion all contribute to the BTE expansion. In the test conducted by K. Surya et. al The BTE improved from diesel to the hydrogen mass flow rate of 0.05 kg/h (KB20H10) is 26.78 % to 28 % at a higher load [6]**.** As a result of the brief quench length, hydrogen blaze falls to the walls of the cylinder more closely than neat diesel. It also burns more quickly and efficiently, raising the temperature of the cylinder and possibly improving combustion and the extraction of fuel energy. Additionally, hydrogen has a much higher calorific value and flame speed than diesel fuel[55]**.**

4.1.2. Brake-specific fuel consumption (BSFC)

BSFC is computed as the mass of fuel used per time unit to produce a given amount of power. In power-producing mode, it gauges an engine's fuel efficiency. Grams per kilowatt-hour (g/kwh) is the unit of measurement for BSFC. When the BSFC is lower, it means that more power is produced with less fuel usage. From neat diesel to 50 % hydrogen enrichment with diesel, the BSFC decreases as injection pressure

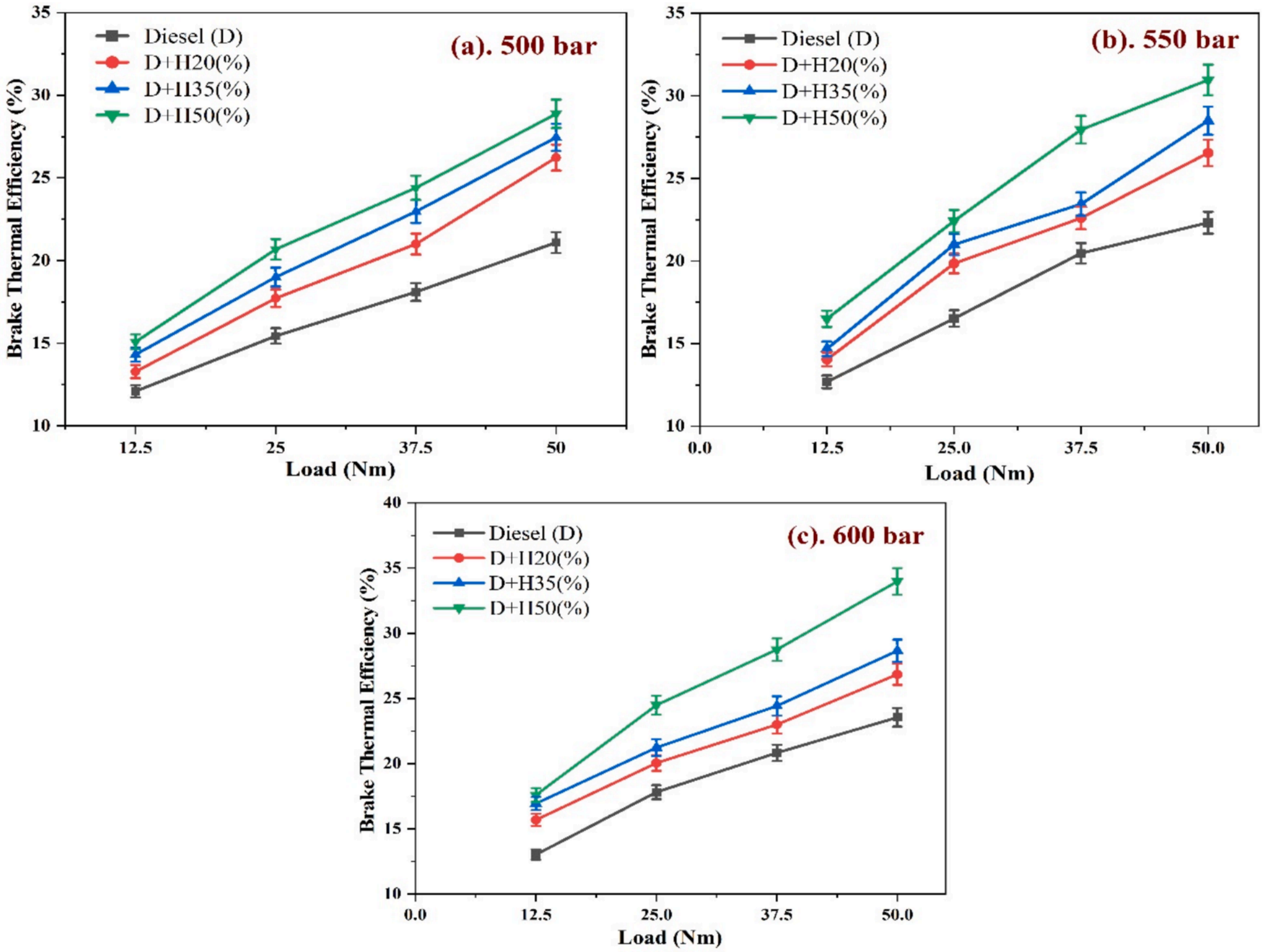


Fig. 3. Variation of load vs BTE for different hydrogen blends at (a) 500 bar (b) 550 bar and (c) 600 bar.

increases.

Fig. 4. (a), (b), and (c) shows that BSFC drops from neat diesel (D) to D + H50% are 400.68 g/kWh and 286.38 g/kWh, which is 28.53 % less than neat diesel, at full load condition (50 Nm) and FIP of 500 bar. Similarly, at 550 bar, BSFC is obtained with 370.36 g/kWh for neat diesel and 255.3 g/kWh for D + H50%. Likewise, at 600 bar FIP, the BSFC values dropped from 365.52 g/kWh for neat diesel to 240.91 g/kWh for D + H50%, which is the lowest values obtained as compared to 500, and 550 bar injection pressure. The lowest BSFC values and the greatest decrease by 34.09 % with 50 % hydrogen enrichment over neat diesel were attained under full load conditions (50 Nm) with an FIP of 600 bar. Because of the high diffusivity of hydrogen fuel mixed with air during the premixed combustion phase, the BSFC values decrease as the FIP increases to 600 bar than 500 bar with an increase in hydrogen enrichment from (20 %) to (50 %), similar results were obtained by N. Seelam et. al, BSFC is maximum Reduction for 24 % HES blend is 18.60 % lower than diesel fuel[55]. Additionally, the combustion chamber temperature rises as a result of the increased hydrogen flame speed and burning velocity. As the in-cylinder temperature rises, there is less fuel accumulation in the combustion chamber and the ignition delay decreases as a result. Due to the narrower quenching gap of hydrogen compared to diesel, the fuel burns completely when the hydrogen flame contacts the cylinder walls. Consequently, in hydrogen diesel dual fuel operation, BSFC decreases as injection pressure and hydrogen enrichment rise.

4.1.3. *Hydrogen energy share (HES)*

The term “hydrogen energy share” describes both the percentage of energy obtained from hydrogen fuel and the fraction of energy released by hydrogen injection. **Equations (2) and (3)**, respectively, are used to determine the hydrogen mass share and hydrogen energy share based on the mass or energy basis [56].

$$\text{Hydrogen mass share} = \frac{m_{hydrogen}}{m_{hydrogen} + m_{fuel}} \tag{2}$$

where m_{fuel} bulk flow rates (kg/sec) of diesel liquid fuel and $m_{hydrogen}$ (kg/sec)inducted hydrogen [57].

$$\text{Hydrogen energy share} = \frac{m_{hydrogen} \times LHV_{hydrogen}}{\left(m_{hydrogen} \times LHV_{hydrogen}\right) + \left(m_{fuel} \times LHV_{fuel}\right)} \tag{3}$$

The term LHV refers to hydrogen’s and diesel fuel’s lower heating values (MJ/kg)[5859].Fig. 5. illustrates the energy share of hydrogen at 600 bar injection pressure, which decreases by 21.78 % to 11.44 % from a lower load (12.5 Nm) to a greater load (50 Nm). This is 10.34 % less than the load of 12.5 Nm at 20 % hydrogen mixed with diesel. The hydrogen energy contribution also decreases with a load of (12.5 to 50) from 25.67 % to 15.63 % at D + H50%, or 10.04 % less than 12.5 Nm. Because the mass flow rate of hydrogen injected into the combustion chamber, which is 0.0331 kg/h (D + H20%) and 0.0828 kg/h (D + H50%), remains constant from lower to higher loading conditions, more power is produced at higher loading conditions by increasing diesel fuel

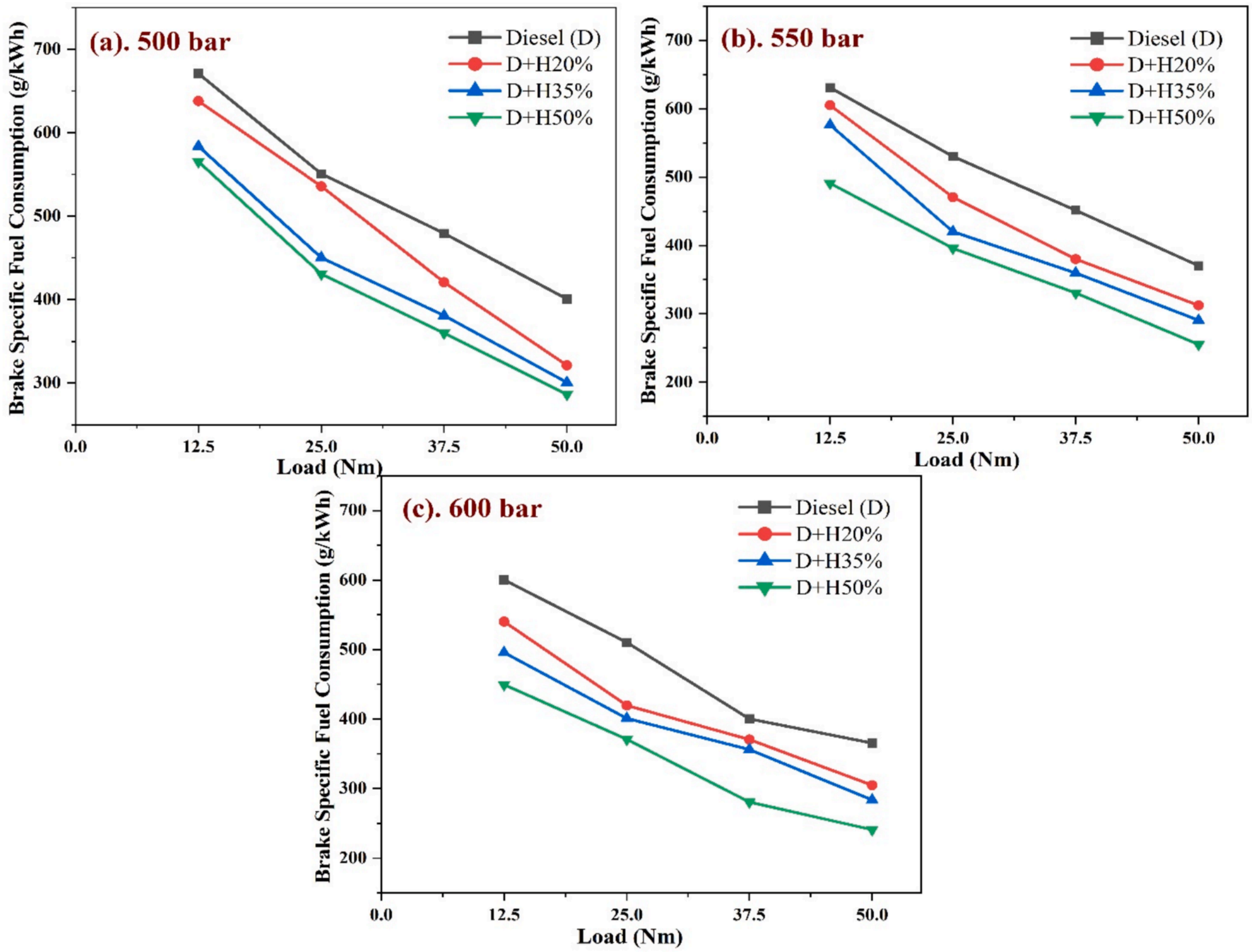


Fig. 4. Variation of load vs BSFC for different hydrogen blends at (a) 500 bar (b) 550 bar and (c) 600 bar.

consumption and decreasing hydrogen share. The hydrogen energy share decreases more with higher loads [56]. The hydrogen energy share increases from D + H20% to D + H50 at load 12.5 Nm, or (21.78 to 25.67 %), representing a 3.89 % increase over D + H20%. The hydrogen energy share increases when the hydrogen enrichment goes from (D + H20% to D + H50%) at the same load because the mass flow rate of hydrogen increased from 0.03312 kg/h to 0.0828 kg/h, respectively, and because the intake air is now hydrogen-enriched, consuming less diesel overall. Increased hydrogen yields more efficient and appropriate combustion, hence increasing the share of hydrogen energy [49].

4.2. Combustion analysis

4.2.1. In-Cylinder pressure

During engine operation, it describes the pressure inside the combustion chamber. In-cylinder pressure varies with different crank angle positions according to the varying injection pressures and hydrogen blends. At full load conditions, the in-cylinder pressure rises in proportion to the injection pressure, resulting in hydrogen enrichment. As a result of the peak cylinder pressure increasing as injection timing advances, pressure curves at advanced injection timing are steeper than those at retarded time[60]. Once the primary fuel is delivered, the homogenous, combustible combination of hydrogen and air injected into the combustion chamber ignites instantly, with the majority of the hydrogen burning in the premixed mode of combustion. In the premixed mode of the combustion phase, the delay period shortens, and pressure and temperature increase. The temperature and pressure inside the cylinder affect how fast hydrogen and air move. According to Fig. 6**. (a), (b),** and **(c)** shows at maximum load condition (50 Nm) and FIP of 500 bar, Peak pressure increases from 61.30 bar to 68.01 bar from neat diesel (D) to 50 % hydrogen enrichment with diesel (D + H50%), or 10.94 % greater than neat diesel. Similarly, maximum peak pressure values improved from neat diesel (D) to D + H50% with a FIP of 550 bar, from 64.22 bar to 72.14 bar, 12.34 % greater than neat diesel. Likewise, at 600 bar, the FIP peak pressure increases from 67.94 bar neat diesel (D) to 76.61 bar (D + H50%), which is the maximum value of peak pressure and 12.76 % higher than neat diesel occurs at 6° CA. At this injection pressure, the peak in-cylinder pressure readings are greater than 500, and 550 bar. Due to immediate hydrogen burning caused by the hydrogen's higher laminar flame speed, the peak pressure value increases when injection pressure increases from 500 bar to 600 bar. The peak pressure of the cylinder was achieved for the optimum hydrogen flow rate of 7.5 lpm is 80 bar and 83 bar for diesel by[61]**.** When D + H50% is used at maximum load during the premixed combustion phase, the combustion chamber gets denser with fuel and burns more quickly.

4.2.2. Heat release rate (HRR)

The HRR is a measure of the rate of combustion. Due to hydrogen's higher calorific value and rapid combustion, which produce a more homogenous mixture for efficient combustion than diesel at higher loads, the HRR rises as injection pressure and hydrogen enrichment rise. Fig. 7**. (a)**, **(b)**, and **(c)** depicts at full load (50 Nm) condition and FIP of

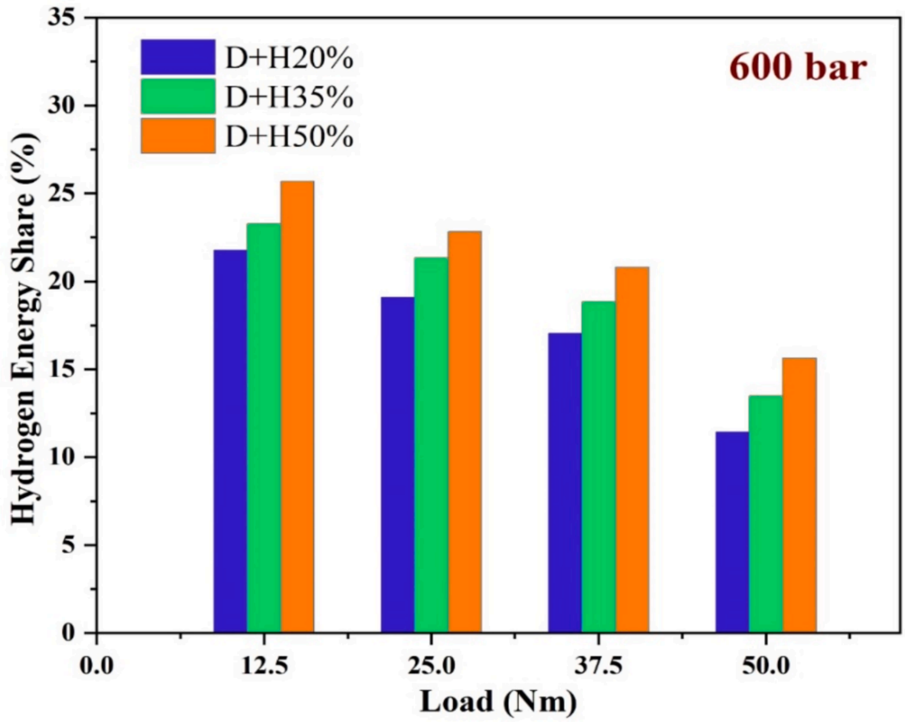


Fig. 5. Variation of load vs HES for different hydrogen blends at 600 bar.

500 bar, the mean HRR value increases by 25.19 % neat diesel (75.92 J/^{o}CA) to D + H50% (95.05 J/^{o}CA). At FIP of 550 bar HRR value improves by 98.15 J/^{o}CA for (D + H50%), which is 25.67 % greater than that of neat diesel (78.12 J/^{o}CA) occurs at the 3° CA position. Due to hydrogen's greater flame temperature and high diffusivity, which allow it to burn quickly in premixed combustion, HRR values have increased from 500 bar to 600 bar. Heat release rates increase with temperature [62]. The highest improvement of Peak values of HRR from 82.44 J/^{o}CA (D) to 103.16 J/^{o}CA (D + H50%) in FIP of 600 bar respectively, which is 29.9 % greater than neat diesel occurs at the 3°CA at maximum load (50 Nm). Elevated HRR is accompanied by increased hydrogen enrichment at higher loads due to the rapid burning of hydrogen during the premixed stage of combustion, which initiates combustion earlier and requires more fuel and air. The results are concluded by R. Senthil Kumar et.al that is highest HRR is 52.79 J/^{o}CA for 8 lpm of hydrogen flow rate than diesel (48.84 J/^{o}CA) at 23 deg. bTDC and full load conditions[34]. In the test conducted by M. T. Chaichan the peak value of HRR was observed at full load, 99.6 J/^{o}CA (7.5 lpm) and 81.5 J/^{o}CA (diesel)[63]. Additionally, increased blend quantity results in higher flame speed. When premixed combustion occurs, hydrogen increases cylinder pressure and HRR more quickly than diesel. This causes the temperature inside the cylinder to rise, which shortens the delay period. The HRR speeds up when hydrogen builds up in the fuel.

4.2.3. Ignition delay

Ignition delay is the period between the start of injection and the start of combustion, it is also a combination of physical and chemical delay [5]. At optimized test conditions of 600 bar and full load conditions, chemical delay is approximately 2–3 times that of physical delay. As the amount of hydrogen enrichment to diesel fuel increases, the ignition delay times comprising of physical and chemical delay also improved due to the higher auto-ignition temperature of hydrogen fuel. In the case of 50 % hydrogen enrichment to diesel, physical and chemical delay times of 6.24 deg. CA and 14.34 deg. CA were recorded as compared to 4.62 deg.CA and 10.63 deg.CA for diesel-only operation as shown in Fig. 8.

4.2.4. Exhaust gas temperature (EGT ^{o}C)

Following the release of hot gases into the exhaust system by the combustion engine, fuel is burned in a combustion chamber in a CI engine. Exhaust gas temperature, or EGT, is expressed in degrees Celsius. **Supplementary Fig. 4.** illustrates how, at 600 bar fuel injection pressure, the EGT value increases from neat diesel (D) to 50 % hydrogen enrichment with diesel (D + H50%), or from 187.45 °C to 229.09 °C at a low load of 12.5 Nm, or 22.21 % greater than neat diesel. Similarly, at 25 Nm, EGT increases by 201.34 °C to 233.18 °C, which is 23.05 % greater than neat diesel. The maximum EGT from diesel to hydrogen (50 %) and the largest increment (39.17 %) over the neat diesel are reached at 50 Nm when EGT climbs from neat diesel (402.85 °C) to D + H50% (560.76 °C). Since hydrogen has a larger caloricity value and diffusive qualities than diesel, it also raises the flame temperature in the combustion chamber, causing the EGT to increase as the load increases (12.5 to 50 Nm) and hydrogen enrichment to climb with diesel (H20% to H50%). Exhaust gas temperature will rise as a result of increased in-cylinder pressure and temperature, which will speed up and provide proper combustion through increases in hydrogen flow rate. In the M.A. Akar et. al. experiment, the temperature rose from 324 °C to 427 °C when the EGT was increased from 4 % to 12 % of HES[64].

4.3. Emission analysis

4.3.1. Oxides of nitrogen (NOx, ppm)

Fig. 9. illustrates how NOx increases from 523.12 ppm to 712.43 pm for neat diesel (D) to D + H50% at 12.5 Nm and 600 bar injection pressure. This is 36.19 % greater than neat diesel and also shows the lowest values obtained. From a lower load to a higher load and from neat diesel (D) to hydrogen enrichment (D + H50%), NOx increases with load. Due to hydrogen's faster flame speed and higher burning temperature than diesel, at full load (50 Nm) NOx was reported to range from 1248.47 ppm to 2124.50 for D to D + H50%. This is 70.17 % more than neat diesel (D) and the maximum NOx at this loading situation[36]. Analogous findings were reported by V. Praveena et al. wherein NOx values increased from 193 ppm to 487 ppm at lower load and from 1254

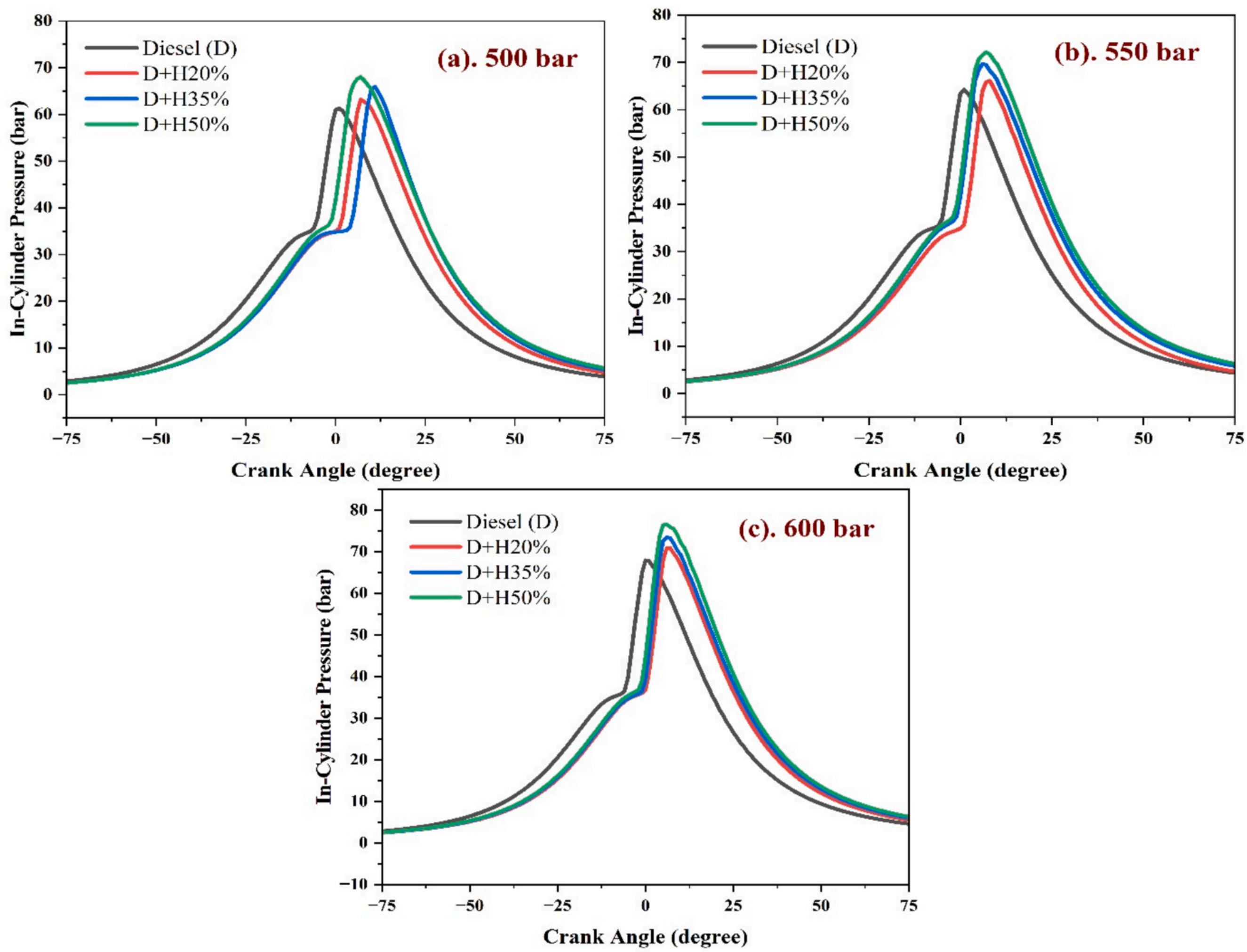


Fig. 6. Variation of crank angle vs in-cylinder pressure for different hydrogen blends at (a) 500 bar (b) 550 bar and (c) 600 bar.

ppm to 1852 ppm at higher load for diesel to 12 % HES because hydrogen injection can change the air–fuel ratio, increasing the amount of oxygen available in the combustion chamber to improve the combustion process, which raises combustion temperatures and increases NOx emissions[65]. High temperatures and oxygen are the two main conditions that cause NOx. Since intake air contains the oxygen required for combustion, diesel engines already run in an oxygen-rich environment. The amount of oxygen available during combustion can be increased by adding hydrogen to pilot fuel diesel, which is a fuel that is high in hydrogen. Higher NOx generation may result from this, particularly if the oxygen-to-fuel ratio is sufficient to enable full combustion at high temperatures [66].

4.3.2. Smoke value (BSN)

When the load increases from lower to higher, smoke forms indicate incomplete fuel burning, which raises the smoke value. The Bosch Smoke Number (BSN) varies with injection pressure; at an ideal 600 bar, the BSN decreases to 0.75 BSN for D to D + H50% at 12.5 Nm, or 50.98 % less than neat diesel (D). This change in BSN is shown in Fig. 10. Smoke value decreases from 4.63 BSN to 2.08 BSN for D to D + H50% at a load of 50 Nm (full load), indicating 55.13 % less smoke generation than neat diesel (D).

Due to the hydrogen enrichment from H20% to H50%, smoke formation is reduced at a higher load because of higher calorific value, and complete combustion than diesel. According to the experimental findings of K. Singh et al. smoke opacity decreased with 40 % hydrogen enrichment at a higher load (BMEP, 5.6 bar) from 64.61 % to 16.25 % [42]. According to S. V. Khandal et al's study, smoke density was reduced by 0.4 g/kWh for 24 % of HES compared to diesel, or 43.08 % less than neat diesel[67]. This is because there is a greater proportion of hydrogen energy in the system, which means that more hydrogen is inducted and less diesel is used. The impact of hydrogen supplementation is lowering in carbon-based emissions with subsequent improvement in NOx emissions[68].

5. Limitations of the present study and future scope

The following list of limitations on hydrogen blending with diesel in twin-cylinder turbocharged CRDI CI engine dual fuel mode is based on current research.

- The combustion properties of hydrogen and diesel differ. It burns faster and ignites more readily, which can cause knocking and unstable combustion in CI engines made primarily for diesel.
- Except for NOx, which is harmful to the environment, hydrogen lowers pollutants like smoke levels by increasing the amount of oxygen in the air–fuel mixture.
- At a steady hydrogen flow rate, the energy contribution of hydrogen has decreased under lower loading situations while increasing the amount of diesel to provide greater power.
- Hydrogen has a low density and may be transported and stored in large-capacity airtight tanks due to its great compressibility under

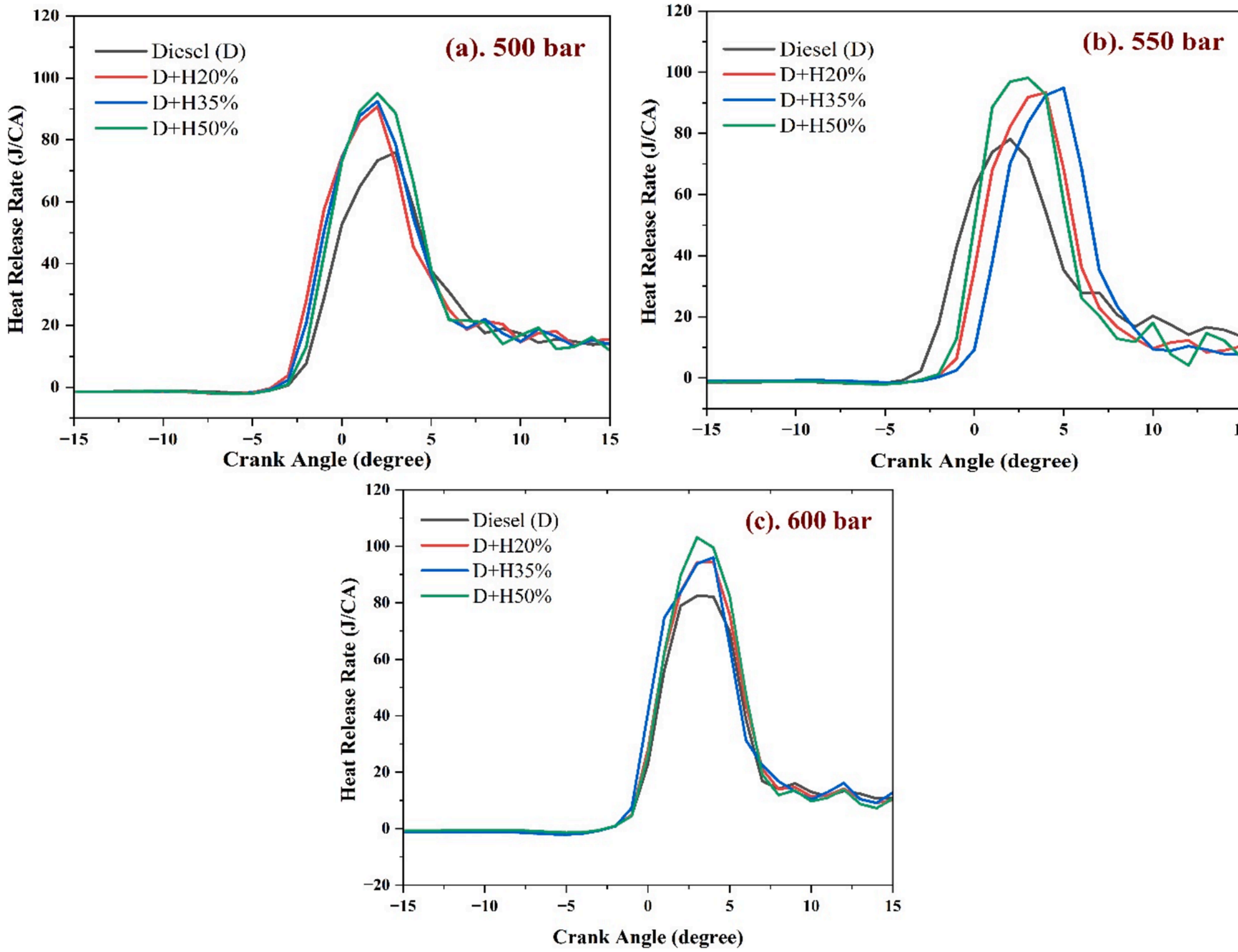


Fig. 7. Variation of crank angle vs HRR for different hydrogen blends at (a) 500 bar (b) 550 bar and (c) 600 bar.

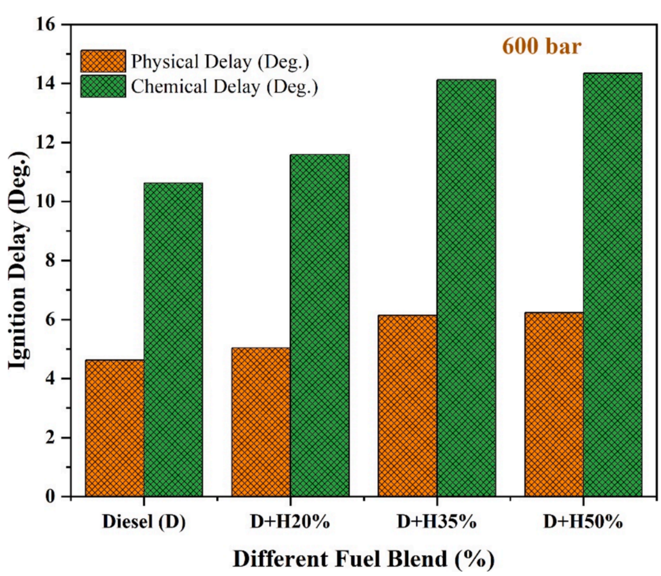


Fig. 8. Ignition delay variation for different hydrogen blends at 600 bar and full load 50 Nm.

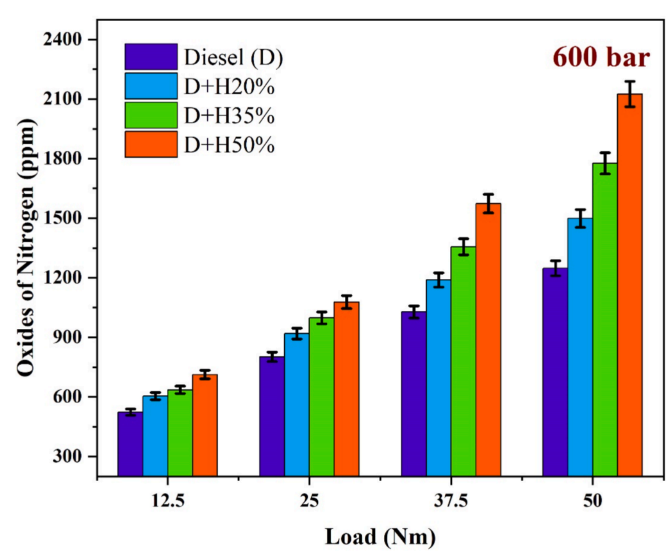


Fig. 9. Variation of load vs NO_x for different hydrogen blends at 600 bar.

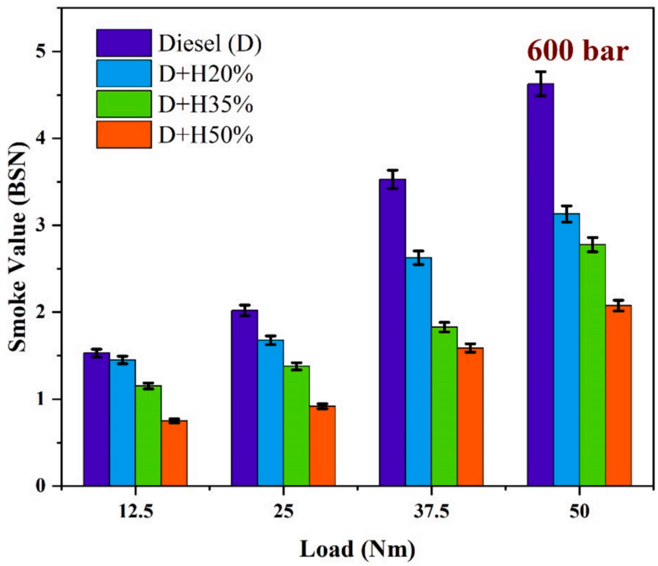


Fig. 10. Variation of load vs smoke value for different hydrogen blends at 600 bar.

high pressure. Therefore, the price of producing these kinds of tanks will be high.

The current work may have the following future applications:

- Creation of innovative engine designs or engine modifications that can manage hydrogen's high diffusivity and quick burning while preserving economy and performance.
- The investigation of cutting-edge emission control technology to limit rising NOx emissions and guarantee adherence to environmental standards.
- Research aims to enhance fuel efficiency and reduce operational concerns by optimizing the blend ratios of hydrogen and diesel.
- Thorough financial analyses to determine whether mixing hydrogen and diesel is more cost-effective than other options, as well as the creation of regulations and incentives to encourage adoption.

6. Conclusions

The present study on turbocharged twin-cylinder dual fuel CRDI CI engines has led us to conclude that effect of increasing FIP from 500 to 600 bar on the engine's performance, combustion, and emission parameters are more significantly affected by hydrogen enhancement (H20%, H35%, and H50%) and an ideal (optimum) fuel injection pressure of 600 bar with D + H50% (optimum). The conclusions are as follows:

- Due to the cumulative effect of higher FIP and better heat content of hydrogen fuel the highest BTE was observed as 33.98 %, (D + H50%) compared to 23.55 % (neat diesel case) at full load conditions.
- Due to the premixed combustion phase an increase in in-cylinder temperature and a reduction in fuel consumption (BSFC) from 365.52 g/kWh (neat diesel case) to 240.91 g/kWh (D + H50% case) at full load conditions.
- Highest in-cylinder pressure, heat release rate and exhaust gas temperature of 76.61 bar, 103.16 J/^{o}CA and 560.76 °C respectively were observed for 50 % hydrogen substitution to diesel fuel owing to the higher energy content and flame speed of hydrogen.
- The Hydrogen Energy Share (HES) values for D + H20% to D + H50% at a load of 12.5 Nm increase from 21.78 % to 25.67 %, the highest values found compared to other loading circumstances (25, 37.5, and 50 Nm) from D + H20% to D + H50%. Consequently, the maximum HES for 50 % hydrogen enrichment applies to all loading conditions because, when hydrogen enrichment is increased from 20 % to 50 %, the hydrogen mass flow rate increases, and the proportion of diesel fuel consumed at the same load decreases.
- Tradeoff characteristics were observed between NOx and BSN with hydrogen substitution to diesel fuel. At 50 % hydrogen substitution to diesel, NOx emissions rose to 2124.50 ppm while BSN perished to 2.08 owing to better combustion characteristics and higher flame temperature of hydrogen.

The present research work validates hydrogen as a secondary fuel for IC engine applications such as power generation, heavy machinery, and transportation, where reliable and efficient engines are essential. Hydrogen enrichment to diesel fuel improves combustion efficiency, reduces reliance on gasoline fuel and helps to achieve sustainable vehicular fuels causing minimum harmful emissions.

CRediT authorship contribution statement

Neetesh Kumar Gupta: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Tikendra Nath Verma:** Supervision, Resources, Project administration.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuel.2025.134592.

Data availability

Data will be made available on request.

References

[1] Fakhari AH, Gharehghani A, Salahi MM, Andwari AM. Numerical investigation of the hydrogen-enriched ammonia-diesel RCCI combustion engine. Fuel 2024;375. https://doi.org/10.1016/j.fuel.2024.132579.

[2] Shrivastava P, Rajak U, Nashine P, Verma TN. Performance and emission characteristics of a compression ignition engine fueled with roselle and karanja biodiesel. Roselle: Production, Processing, Products and Biocomposites 2021: 165–76. https://doi.org/10.1016/B978-0-323-85213-5.00015-9.

[3] Shirneshan A, Kanberoglu B, Gonca G. Experimental investigation and parametric modeling of the effect of alcohol addition on the performance and emissions characteristics of a diesel engine fueled with biodiesel-diesel-hydrogen fuel mixtures. Fuel 2025;381. https://doi.org/10.1016/j.fuel.2024.133489.

[4] Hamza NH, Al-Dawody MF, Al-Farhany KA, Rajak U, Verma TN. Impact of using different biofuels on the characteristics of turbocharged diesel engine: an application towards mechanical engineering. Environ Dev Sustain 2023. https://doi.org/10.1007/s10668-023-03923-5.

[5] Cheng C, Faurskov Cordtz R, Dyhr Pedersen T, Winther K, Langballe Førby N, Schramm J. Investigation of combustion characteristics, physical and chemical ignition delay of methanol fuel in a heavy-duty turbo-charged compression ignition engine. Fuel 2023;348. https://doi.org/10.1016/j.fuel.2023.128536.

[6] Kanth S, Debbarma S, Das B. Experimental investigations on the effect of fuel injection parameters on diesel engine fuelled with biodiesel blend in diesel with hydrogen enrichment. Int J Hydrogen Energy 2022;47(83):35468–83. https://doi.org/10.1016/j.ijhydene.2022.08.095.

[7] Dey S, Sreenivasulu A, Veerendra GTN, Rao KV, Babu PSSA. "Renewable energy present status and future potentials in India: an overview". Elsevier B.V; 2022. 10.1016/j.igd.2022.100006.

[8] Garzón Baquero JE, Bellon Monsalve D. From fossil fuel energy to hydrogen energy: transformation of fossil fuel energy economies into hydrogen economies through social entrepreneurship. Int J Hydrogen Energy 2024;54:574–85. https://doi.org/10.1016/j.ijhydene.2023.06.123.

[9] Teoh YH, et al. A review on production and implementation of hydrogen as a green fuel in internal combustion engines. Fuel 2023;333. https://doi.org/10.1016/j.fuel.2022.126525.
[10] Shi C, Ji C, Wang S, Yang J, Wang H. Experimental and numerical study of combustion and emissions performance in a hydrogen-enriched Wankel engine at stoichiometric and lean operations. Fuel 2021;291. https://doi.org/10.1016/j.fuel.2021.120181.
[11] Sindhu R, Prabhat ST, Hiep BT, Chinnathambi A, Alharbi SA. Experimental assessment of cork based Botryococcus braunii microalgae blends and hydrogen in modified multicylinder diesel engine. Fuel 2024;359. https://doi.org/10.1016/j.fuel.2023.130468.
[12] Xu X, Zhou Q, Yu D. "The future of hydrogen energy: bio-hydrogen production technology". Elsevier Ltd; 2022. 10.1016/j.ijhydene.2022.07.261.
[13] Bhagat RN, Sahu KB, Ghadai SK, Kumar CB. "A review of performance and emissions of diesel engine operating on dual fuel mode with hydrogen as gaseous fuel". Elsevier Ltd; 2023. 10.1016/j.ijhydene.2023.03.251.
[14] Halewadimath SS, Yaliwal VS, Banapurmath NR, Sajjan AM. Influence of hydrogen enriched producer gas (HPG) on the combustion characteristics of a CRDI diesel engine operated on dual-fuel mode using renewable and sustainable fuels. Fuel 2020;270. https://doi.org/10.1016/j.fuel.2020.117575.
[15] Onorati A, et al. "The role of hydrogen for future internal combustion engines". SAGE Publications Ltd; 2022. 10.1177/14680874221081947.
[16] Singh K, Verma TN, Dwivedi G, Shukla AK. "Hydrogen production, storage, and CI Engine utilisation: a global perspective". Institution of Chemical Engineers; 2024. 10.1016/j.psep.2024.07.110.
[17] Z. Stępień, "A comprehensive overview of hydrogen-fueled internal combustion engines: Achievements and future challenges," Oct. 01, 2021, MDPI. doi: 10.3390/en14206504.
[18] Babay MA, Adar M, Chebak A, Mabrouki M. Forecasting green hydrogen production: an assessment of renewable energy systems using deep learning and statistical methods. Fuel 2025;381. https://doi.org/10.1016/j.fuel.2024.133496.
[19] Nam JY, et al. Hydrogen-rich gas production from disposable COVID-19 mask by steam gasification. Fuel 2023;331. https://doi.org/10.1016/j.fuel.2022.125720.
[20] I. - International Energy Agency, "Global Hydrogen Review 2023," 2023. [Online]. Available: www.iea.org.
[21] Uyar TS, Beşikci D. Integration of hydrogen energy systems into renewable energy systems for better design of 100% renewable energy communities. Int J Hydrogen Energy 2017;42(4):2453–6. https://doi.org/10.1016/j.ijhydene.2016.09.086.
[22] Abdin Z, Zafaranloo A, Rafiee A, Mérida W, Lipiński W, Khalilpour KR. "Hydrogen as an energy vector". Elsevier Ltd; 2020. 10.1016/j.rser.2019.109620.
[23] I. Energy Agency, "Net Zero by 2050 - A Roadmap for the Global Energy Sector," 2050. [Online]. Available: www.iea.org/t&c/.
[24] "INDIA'S GREEN HYDROGEN REVOLUTION-An Ambitious Approach," 2024.
[25] "Department of Science and Technology.".
[26] Harichandan S, Kar SK, Rai PK. "A systematic and critical review of green hydrogen economy in India". Elsevier Ltd; 2023. 10.1016/j.ijhydene.2023.04.316.
[27] Tiwari C, Verma TN, Dwivedi G, Verma P. "Energy-exergy analysis of diesel engine fueled with microalgae biodiesel-diesel blend". Applied Sciences (Switzerland) 2023;13(3). https://doi.org/10.3390/app13031857.
[28] Prajapati LK, Tiwari C, Verma TN, Dwivedi G, Paliwal D. Production and testing of mahua oil–based biodiesel synthesized through heterogeneous catalyst using experimental and numerical method. Environ Sci Pollut Res 2024. https://doi.org/10.1007/s11356-024-33558-6.
[29] Tiwari C, Dwivedi G, Verma TN. Sustainability evaluation, optimization and research dynamics of microalgae methyl ester in a research diesel engine. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering 2023. https://doi.org/10.1177/09544089231162318.
[30] Bayramoğlu K, Yılmaz S. Emission and performance estimation in hydrogen injection strategies on diesel engines. Int J Hydrogen Energy 2021;46(57):29732–44. https://doi.org/10.1016/j.ijhydene.2020.08.135.
[31] Thiyagarajan S, et al. Effect of hydrogen on compression-ignition (CI) engine fueled with vegetable oil/biodiesel from various feedstocks: a review. Int J Hydrogen Energy 2022;47(88):37648–67. https://doi.org/10.1016/j.ijhydene.2021.12.147.
[32] Wang H, Wang B, Yang C, Hu D, Duan B, Wang Y. Study on dual injection strategy of diesel ignition ammonia/hydrogen mixture fuel engine. Fuel 2023;348. https://doi.org/10.1016/j.fuel.2023.128526.
[33] Cernat A, Pana C, Negurescu N, Nutu C, Fuiorescu D, Lazaroiu G. "Aspects of an experimental study of hydrogen use at automotive diesel engine". Elsevier Ltd; 2023. 10.1016/j.heliyon.2023.e13889.
[34] Kumar RS, Loganathan M, Gunasekaran EJ. Performance, emission and combustion characteristics of CI engine fuelled with diesel and hydrogen. Front Energy 2015;9(4):486–94. https://doi.org/10.1007/s11708-015-0368-4.
[35] Saravanan N, Nagarajan G. Performance and emission studies on port injection of hydrogen with varied flow rates with Diesel as an ignition source. Appl Energy 2010;87(7):2218–29. https://doi.org/10.1016/j.apenergy.2010.01.014.
[36] Tsujimura T, Suzuki Y. The utilization of hydrogen in hydrogen/diesel dual fuel engine. Int J Hydrogen Energy 2017;42(19):14019–29. https://doi.org/10.1016/j.ijhydene.2017.01.152.
[37] Nag S, Sharma P, Gupta A, Dhar A. Experimental study of engine performance and emissions for hydrogen diesel dual fuel engine with exhaust gas recirculation. Int J Hydrogen Energy 2019;44(23):12163–75. https://doi.org/10.1016/j.ijhydene.2019.03.120.
[38] Dahake MR, Malkhede DN. "Experimental investigation of performance and emissions of CRDI diesel engine in dual fuel mode by hydrogen induction and diesel injection coupled with exhaust gas recirculation". In: Materials Today: Proceedings. Elsevier Ltd; 2021. p. 2814–9. 10.1016/j.matpr.2021.02.653.
[39] Rajak U, Nashine P, Verma TN, Veza I, Ağbulut Ü. Numerical and experimental investigation of hydrogen enrichment in a dual-fueled CI engine: a detailed combustion, performance, and emission discussion. Int J Hydrogen Energy 2022;47(76):32741–52. https://doi.org/10.1016/j.ijhydene.2022.07.144.
[40] Verma S, Das LM, Bhatti SS, Kaushik SC. A comparative exergetic performance and emission analysis of pilot diesel dual-fuel engine with biogas, CNG and hydrogen as main fuels. Energy Convers Manag 2017;151:764–77. https://doi.org/10.1016/j.enconman.2017.09.035.
[41] Verma S, Das LM, Kaushik SC. Effects of varying composition of biogas on performance and emission characteristics of compression ignition engine using exergy analysis. Energy Convers Manag 2017;138:346–59. https://doi.org/10.1016/j.enconman.2017.01.066.
[42] Singh K, Dwivedi G, Verma TN, Shukla AK. Energy, exergy, emissions and sustainability assessment of hydrogen supplemented diesel dual fuel turbocharged common rail direct injection diesel engine. Int J Hydrogen Energy 2024. https://doi.org/10.1016/j.ijhydene.2024.05.080.
[43] Gürbüz H, Akçay İH. Evaluating the effects of boosting intake-air pressure on the performance and environmental-economic indicators in a hydrogen-fueled SI engine. Int J Hydrogen Energy 2021;46(56):28801–10. https://doi.org/10.1016/j.ijhydene.2021.06.099.
[44] Das S, Das B. Effect of injection parameters on the hydrogen enriched dual-fuel CRDI diesel engine. Energy Sources Part A 2023;45(4):10176–99. https://doi.org/10.1080/15567036.2023.2240256.
[45] Khandal SV, Yunus Khan TM, Kamangar S, Baig MAA, Ahmed N J S. "Effects of hydrogen flow rate, injection pressure and EGR on performance of common rail direct injection (CRDi) engine in dual fuel mode". Front Eng Built Environ 2021;1(1):81–96. https://doi.org/10.1108/febe-02-2021-0007.
[46] Gnanamoorthi V, Vimalananth VT. Effect of hydrogen fuel at higher flow rate under dual fuel mode in CRDI diesel engine. Int J Hydrogen Energy 2020;45(33):16874–89. https://doi.org/10.1016/j.ijhydene.2020.04.145.
[47] Kumar M, Bhowmik S, Paul A. Effect of pilot fuel injection pressure and injection timing on combustion, performance and emission of hydrogen-biodiesel dual fuel engine. Int J Hydrogen Energy 2022;47(68):29554–67. https://doi.org/10.1016/j.ijhydene.2022.06.260.
[48] Kanth S, Ananad T, Debbarma S, Das B. Effect of fuel opening injection pressure and injection timing of hydrogen enriched rice bran biodiesel fuelled in CI engine. Int J Hydrogen Energy 2021;46(56):28789–800. https://doi.org/10.1016/j.ijhydene.2021.06.087.
[49] Köse H, Ciniviz M. An experimental investigation of effect on diesel engine performance and exhaust emissions of addition at dual fuel mode of hydrogen. Fuel Process Technol 2013;114:26–34. https://doi.org/10.1016/j.fuproc.2013.03.023.
[50] Saravanan B, Asokan MA. Impact of fuel injection parameters and hydrogen enrichment on CI engine characteristics fueeled with Ceiba pentandra biodiesel. Energy Sources Part A 2024;46(1):3734–47. https://doi.org/10.1080/15567036.2024.2320760.
[51] Kakran S, Kaushal R, Bajpai VK. Experimental study and optimization of performance characteristics of compression ignition hydrogen engine with diesel pilot injection. Int J Hydrogen Energy 2023;48(86):33705–18. https://doi.org/10.1016/j.ijhydene.2023.05.103.
[52] Tarafdar A, Majumder P, Deb M, Bera UK. Performance-emission optimization in a single cylinder CI-engine with diesel hydrogen dual fuel: a spherical fuzzy MARCOS MCGDM based Type-3 fuzzy logic approach. Int J Hydrogen Energy 2023;48(73):28601–27. https://doi.org/10.1016/j.ijhydene.2023.04.019.
[53] Lata DB, Misra A, Medhekar S. Effect of hydrogen and LPG addition on the efficiency and emissions of a dual fuel diesel engine. Int J Hydrogen Energy 2012;37(7):6084–96. https://doi.org/10.1016/j.ijhydene.2012.01.014.
[54] Aceves SM, et al. High-density automotive hydrogen storage with cryogenic capable pressure vessels. Int J Hydrogen Energy 2010;35(3):1219–26. https://doi.org/10.1016/j.ijhydene.2009.11.069.
[55] Seelam N, Gugulothu SK, Reddy RV, Bhasker B, Kumar Panda J. Exploration of engine characteristics in a CRDI diesel engine enriched with hydrogen in dual fuel mode using toroidal combustion chamber. Int J Hydrogen Energy 2022;47(26):13157–67. https://doi.org/10.1016/j.ijhydene.2022.02.056.
[56] Chintala V, Subramanian KA. Experimental investigations on effect of different compression ratios on enhancement of maximum hydrogen energy share in a compression ignition engine under dual-fuel mode. Energy 2015;87:448–62. https://doi.org/10.1016/j.energy.2015.05.014.
[57] Ozcanli M, Akar MA, Calik A, Serin H. Using HHO (Hydroxy) and hydrogen enriched castor oil biodiesel in compression ignition engine. Int J Hydrogen Energy 2017;42(36):23366–72. https://doi.org/10.1016/j.ijhydene.2017.01.091.
[58] Aldhaidhawi M, Chiriac R, Bădescu V, Descombes G, Podevin P. Investigation on the mixture formation, combustion characteristics and performance of a Diesel engine fueled with Diesel, Biodiesel B20 and hydrogen addition. Int J Hydrogen Energy 2017;42(26):16793–807. https://doi.org/10.1016/j.ijhydene.2017.01.222.
[59] Agarwal AK, Srivastava DK, Dhar A, Maurya RK, Shukla PC, Singh AP. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel 2013;111:374–83. https://doi.org/10.1016/j.fuel.2013.03.016.
[60] Geo VE, et al. "CO2 reduction in a common rail direct injection engine using the combined effect of low carbon biofuels, hydrogen and a post combustion carbon capture system". Energy Sources Part A 2021. https://doi.org/10.1080/15567036.2021.1974128.
[61] Chaichan MT. Performance and emission characteristics of CIE using hydrogen, biodiesel, and massive EGR. Int J Hydrogen Energy 2018;43(10):5415–35. https://doi.org/10.1016/j.ijhydene.2017.09.072.

[62] Jegadheesan C, Somasundaram P, Meenakshipriya B, Vignesh UP. Investigation effect of hydrogen addition on the performance and exhaust emissions of Pongamia pinnata biodiesel fueled compression ignition engine. Int J Green Energy 2017;14(15):1256–68. https://doi.org/10.1080/15435075.2017.1399134.

[63] Rahman MA, Ruhul AM, Aziz MA, Ahmed R. Experimental exploration of hydrogen enrichment in a dual fuel CI engine with exhaust gas recirculation. Int J Hydrogen Energy 2017;42(8):5400–9. https://doi.org/10.1016/j.ijhydene.2016.11.109.

[64] Akar MA, Kekilli E, Bas O, Yildizhan S, Serin H, Ozcanli M. Hydrogen enriched waste oil biodiesel usage in compression ignition engine. Int J Hydrogen Energy 2018;43(38):18046–52. https://doi.org/10.1016/j.ijhydene.2018.02.045.

[65] Praveena V, Shobana Bai FJJ, Balasubramanian D, Devarajan Y, Aloui F, Varuvel EG. Experimental assessment on the performance, emission and combustion characteristics of a safflower oil fueled CI engine with hydrogen gas enrichment. Fuel 2023;334. https://doi.org/10.1016/j.fuel.2022.126682.

[66] Zhang Z, et al. The effects of Fe2O3 based DOC and SCR catalyst on the combustion and emission characteristics of a diesel engine fueled with biodiesel. Fuel 2021;290. https://doi.org/10.1016/j.fuel.2020.120039.

[67] Khandal SV, Ağbulut Ü, Afzal A, Sharifpur M, Abdul Razak K, Khalilpoor N. Influences of hydrogen addition from different dual-fuel modes on engine behaviors. Energy Sci Eng 2022;10(3):881–91. https://doi.org/10.1002/ese3.1065.

[68] A. Singh, N. Kumar, P. Kumar, and A. K. Singh, “Performance analysis of a ci engine in dual mode with hydrogen and diesel.” [Online]. Available: https://www.researchgate.net/publication/274377291.