

Performance And Emission Characteristics Of A DI Diesel Engine Using Hydrogen And Cotton Seed Methyl Ester Blends

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Abstract- Engine exhaust emissions are a major environmental concern, motivating the search for sustainable and cleaner alternatives to conventional diesel fuel. While vegetable oil-based fuels are renewable and eco-friendly, their direct use in diesel engines often results in higher smoke emissions and lower thermal efficiency. One promising strategy to overcome these drawbacks is the induction of a clean gaseous fuel, such as hydrogen, into the intake manifold to enhance the combustion process. In this study, the performance, combustion, and emission characteristics of a single-cylinder, four-stroke, air-cooled, variable compression ratio (VCR) diesel engine were evaluated using a dual-fuel approach. Cotton Seed Methyl Ester (CSME B20) was used as the primary fuel, with hydrogen inducted at flow rates of 4 LPM and 8 LPM through the intake manifold. The results were compared with those from conventional diesel operation. The brake thermal efficiency (BTE) improved from 33.35% for diesel to 33.65% and 35.12% with 4 LPM and 8 LPM hydrogen enrichment, respectively, under full-load conditions. The high flame propagation speed of hydrogen enhanced air-fuel mixing and combustion, leading to improved thermal efficiency and reduced brake specific fuel consumption (BSFC), which reached 0.24 kg/kW·hr at 8 LPM. However, a marginal rise in NO_x emissions (up to 2120 ppm) was observed due to elevated combustion temperatures.

Conversely, hydrogen enrichment significantly lowered smoke opacity (from 66.9% at 4 LPM to 61.7% at 8 LPM), carbon monoxide (0.019% at full load), and unburnt hydrocarbons. Overall, CSME B20 with 8 LPM hydrogen exhibited the best performance, indicating its potential as a cleaner and efficient alternative fuel for compression ignition engines.

Keywords- Cotton Seed Methyl Ester (CSME), Hydrogen enrichment, Dual-fuel diesel engine, Brake thermal efficiency (BTE), Brake specific fuel consumption (BSFC), Emission characteristics, Alternative fuels.

I. INTRODUCTION

The escalating global energy demand, coupled with the rapid depletion of fossil fuel reserves and the intensifying threat of environmental pollution, has compelled researchers to explore sustainable and cleaner alternatives to conventional petroleum-based fuels. Diesel engines remain the backbone of the transportation, agricultural, and power generation sectors due to their robustness and high thermal efficiency, yet they are also major contributors to greenhouse gas emissions and urban air pollution. This dependence on finite fossil resources poses serious challenges to long-term energy security and environmental sustainability.

Among the available renewable options, biodiesel derived from non-edible vegetable oils has gained considerable attention owing to its biodegradability, lower sulfur content, and potential to reduce carbon-based emissions. Cotton seed oil, widely available in India and other tropical regions, offers significant promise as a biodiesel feedstock because of its high oil content (40–45%) and domestic availability. However, the use of biodiesel alone often results in higher viscosity, incomplete combustion, elevated smoke levels, and marginally lower thermal efficiency compared to diesel.

To overcome these limitations, the supplementation of biodiesel with hydrogen—a clean, carbon-free energy carrier—has emerged as an effective strategy to enhance combustion efficiency and emission performance. Hydrogen possesses a high flame propagation speed, wide flammability limits, and superior diffusivity, which collectively promote better air-fuel mixing and more complete combustion.

This study investigates the performance, combustion, and emission characteristics of a compression ignition engine operating on Cotton Seed Methyl Ester (CSME B20) blended fuel with hydrogen enrichment at flow rates of 4 LPM and 8 LPM, aiming to establish a viable and cleaner dual-fuel alternative for diesel engine applications.

II. RESEARCH IDEA

The concept for this research for this study originated from the growing global concern over the depletion of fossil fuels and the need to reduce the environmental impact of diesel engine emissions. A broad review of alternative energy sources was undertaken, focusing on renewable bio-based fuels such as vegetable oils, biodiesel, alcohols, and biogas, and assessing their suitability for use in compression ignition (CI) engines. Among these, cotton seed oil was identified as a promising feedstock for biodiesel production because of its abundant availability in India, high oil content, renewability, and lower sulfur emissions.

Simultaneously, hydrogen emerged as a clean, carbon-free energy carrier with high flame speed, wide flammability limits, and superior diffusivity, making it a suitable supplementary fuel to enhance combustion and thermal efficiency in dual-fuel operation. An extensive literature survey was then conducted on biodiesel and hydrogen enrichment in diesel engines to evaluate their individual effects on performance, combustion, and emissions. However, despite extensive research on biodiesel and hydrogen enrichment individually, very few studies have investigated their combined application in diesel engines—particularly using cotton seed methyl ester (CSME) as the primary fuel. Most prior studies focused on other vegetable oil-based biodiesels such as jatropha, mahua, or rubber seed, often using higher hydrogen flow rates without assessing the effects at lower, practically feasible enrichment levels.

Furthermore, many works reported only overall performance and tailpipe emissions, with limited analysis of in-cylinder combustion behavior, pressure development, and load-wise fuel consumption. The trade-offs between improvements in efficiency and the rise in NO_x emissions with hydrogen addition also remain insufficiently quantified for CSME blends. This identified knowledge gap forms the basis of the present study, which investigates the combined use of CSME B20 with low-rate hydrogen enrichment (4 LPM and 8 LPM) in a DI VCR diesel engine to enhance performance while reducing harmful emissions.

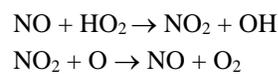
III. EMISSION DYNAMICS AND CONTROL TECHNIQUES

Diesel engines, extensively utilized across transportation, industrial, and agricultural sectors, are recognized as major sources of pollutants including particulate matter (PM), smoke, oxides of nitrogen (NO_x), carbon monoxide (CO), hydrocarbons (HC), and sulfur oxides (SO_x). The generation of these emissions is governed by several

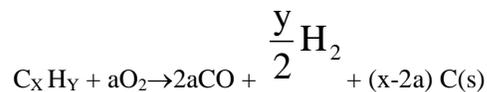
factors, such as incomplete combustion, fuel injection timing, air-fuel ratio, fuel atomization, and in-cylinder combustion conditions. Notably, NO_x formation is primarily influenced by high combustion temperatures, whereas particulate matter and HC emissions predominantly arise from incomplete combustion and pyrolysis of fuel compounds. The principal reactions responsible for NO formation from molecular nitrogen are:



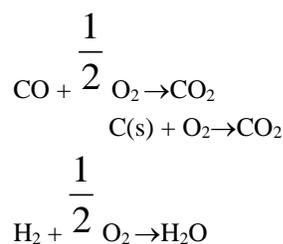
NO can further convert to NO₂ via:



Particulate matter or soot formation occurs primarily under fuel-rich conditions and can be expressed as:



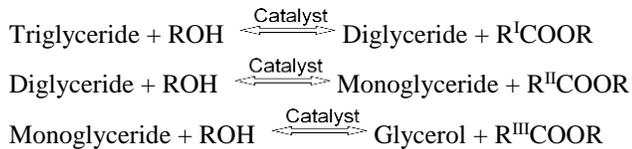
Subsequent oxidation of CO, H₂, and unburned carbon in the diffusion flame produces:



To mitigate these emissions, extensive research has explored diesel engine control strategies encompassing: design modifications (swirl and pre-combustion chambers, turbocharging, optimized compression ratios), operating parameter optimization (engine load, injection timing, injection pressure, and rate), in-cylinder treatments (catalyst coating, fuel modification, and exhaust gas recirculation), and after-treatment technologies (trap oxidizers, particulate filters). While these interventions have demonstrated efficacy in reducing pollutants, they often necessitate trade-offs between engine performance, fuel efficiency, and environmental compliance.

Concurrently, the pressing need to reduce reliance on fossil fuels and mitigate environmental impacts has spurred

significant interest in alternative fuels. Among these, biodiesel, derived from renewable feedstocks such as vegetable oils and animal fats, offers considerable advantages. Its oxygenated nature facilitates more complete combustion, reducing CO, HC, and particulate emissions, while its biodegradability and non-toxicity enhance environmental sustainability. Biodiesel production through transesterification—the reaction of triglycerides with alcohol in the presence of a catalyst—achieves high conversion efficiency:



Where, R = $-\text{CH}_3/\text{C}_2\text{H}_5$. Typically, a 5:1 molar ratio of alcohol to triglyceride yields 95–98% ester efficiency.

Within this context, cotton seed oil has emerged as a particularly promising feedstock in India due to its abundant availability, high oil content, renewability, and low sulfur content. Additionally, hydrogen has been identified as a clean, carbon-free supplementary fuel, characterized by high flame speed, wide flammability limits, and superior diffusivity, which can enhance in-cylinder combustion and thermal efficiency. Despite extensive studies on biodiesel and hydrogen enrichment individually, the combined application of cotton seed methyl ester (CSME) biodiesel with low-rate hydrogen enrichment in diesel engines remains underexplored, particularly in terms of in-cylinder combustion characteristics, load-wise fuel consumption, and NO_x emission trade-offs.

This research seeks to bridge this gap by investigating the performance, combustion, and emission characteristics of a DI VCR diesel engine operating with CSME B20 blended biodiesel supplemented by low-rate hydrogen enrichment (4–8 LPM). The study aims to provide a practical and sustainable approach to improving diesel engine efficiency, minimizing environmental impact, and advancing the adoption of renewable fuels and cleaner combustion technologies in practical applications.

IV. METHODOLOGY

Cottonseed oil was selected as the primary feedstock for biodiesel production owing to its abundant local availability in the Salem district, relatively low cost, and high oil content (~40–45%). Direct use of raw vegetable oils in diesel engines is not advisable due to their high viscosity, low volatility, and the presence of free fatty acids (FFA), phospholipids, sterols, and moisture, all of which can lead to

injector coking, piston ring sticking, and excessive carbon deposits. To overcome these drawbacks and make it compatible with compression ignition (CI) engines, the oil was converted into cottonseed methyl ester (CSME) via an alkali-catalyzed transesterification process.

Materials:

The raw materials and laboratory apparatus employed in this study included:

- Cottonseed Oil (1 L): Obtained from local mills; used as the triglyceride feedstock.
- Methanol (200 mL, 99 % pure): A polar, short-chain alcohol used to cleave triglycerides into methyl esters (biodiesel) and glycerol.
- Potassium Hydroxide (KOH, 14 g): A strong alkali catalyst that forms potassium methoxide to accelerate ester formation.
- Hot Plate with Magnetic Stirrer: Provided controlled heating (up to 750 °C) and agitation to ensure homogenous mixing and heat transfer.
- Glassware: Separating funnel (1000 mL), measuring beakers, thermometer, and precision weighing balance.

Methodological Framework:

The biodiesel was synthesized using the base-catalyzed transesterification technique, which is widely recognized for producing high conversion yields under mild operating conditions.

Chemical Reactions:

The molar ratio of oil to methanol was maintained at 1:10, which favors the forward reaction while limiting unreacted triglycerides. Catalyst loading was kept at approximately 1.4 wt % of oil to achieve rapid reaction kinetics while avoiding excessive soap formation. The reaction temperature was maintained at around 60 °C, below methanol's boiling point, to balance the competing effects of enhanced kinetics and methanol evaporation.

Process Considerations:

- Mixing & Mass Transfer: The immiscibility of oil and methanol can limit reaction rates; vigorous magnetic stirring was applied to enhance interfacial contact and reduce mass transfer resistance.

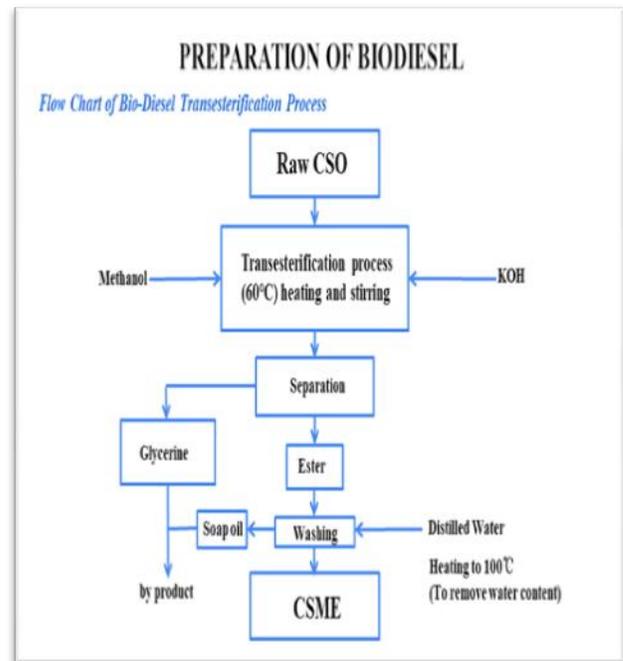
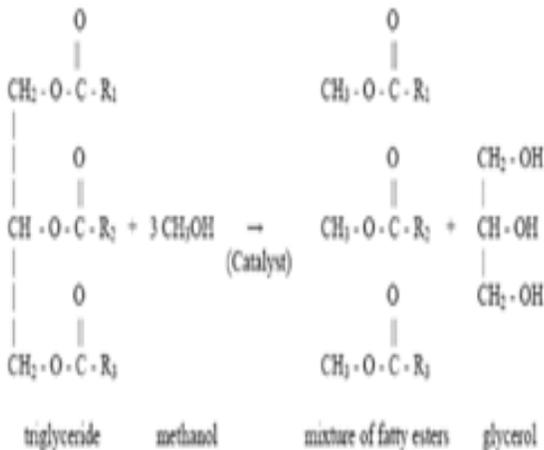
- Reaction Kinetics: Maintaining adequate residence time ensured complete conversion of triglycerides to fatty acid methyl esters (FAME).
- Phase Separation: After reaction, the denser glycerol by-product was separated from the lighter methyl ester phase by gravity settling using a separating funnel.
- Purification & Drying: The crude methyl ester was washed repeatedly with warm deionized water to remove residual catalyst, methanol, and soaps, and then dried to remove entrained moisture, ensuring stability during storage.

This approach reduces viscosity by almost an order of magnitude, enhances volatility, improves ignition quality, and makes CSME suitable for CI engine operation.

The process achieved a typical yield of ~800 mL CSME from 1000 mL of raw oil.

Safety & Handling:

Both methanol and KOH are hazardous, appropriate PPE (gloves, goggles, fume hood) was used. The exothermic dissolution of KOH in methanol was managed by slow addition and controlled cooling. The separated glycerol was stored safely and not released into the environment.



Characterization of CSME Properties:

To ensure fuel quality, the physicochemical properties of the prepared CSME were evaluated in accordance with ASTM standards. These properties govern cold-flow behavior, combustion quality, safety, and energy content—factors essential for diesel engine applications.

Testing Methods:

Property	Apparatus	ASTM Method
Density	Hydrometer	ASTMD4052
Kinematic Viscosity	Redwood Viscometer	ASTM D445
Flash & Fire Point	Pensky-Martens Apparatus	ASTM D93
Cloud & Pour Point	Cloud & Pour Point Apparatus	ASTM D941
Calorific Value	Bomb Calorimeter	ASTM D240
Cetane Number	Ignition Quality Tester	ASTM D613

Measured Properties:

Property	Diesel	CSME (B100)	Hydrogen
Density @ 30 °C (kg/m ³)	0.830	0.941	0.083
Kinematic Viscosity @ 40 °C (mm ² /s)	3.294	5.31	0.00011
Flash Point (°C)	68	117	–
Fire Point (°C)	78	145	–
Cloud Point (°C)	2	3	–
Pour Point (°C)	-15	-3	–
Gross Calorific Value (kJ/kg)	44000	41600	150000
Cetane Number	51	47	–

Interpretation of Properties:

- Cloud & Pour Point: Determine cold flow behavior and pumpability. CSME showed a cloud point of 3 °C and pour point of -3 °C, suitable for moderate climates.
- Flash & Fire Point: Reflect safety during storage and handling. CSME's higher flash (117 °C) and fire point (145 °C) reduce flammability hazards.
- Density & Viscosity: Slightly higher than diesel, aiding in lubrication but within permissible engine limits.
- Cetane Number: Indicates ignition quality; CSME (47) is slightly lower than diesel but sufficient for smooth CI engine operation.
- Calorific Value: Slightly lower than diesel, yet adequate for good thermal efficiency. Hydrogen, used later as a supplementary inducted fuel, has a much higher energy content (~150 MJ/kg), supporting enhanced combustion.

V. EXPERIMENTAL PROCEDURE

Engine Test Setup:

The experimental investigation was carried out on a **single-cylinder, four-stroke, water-cooled, direct-injection (DI) diesel engine** (Kirloskar TV1 type), coupled with an **eddy current dynamometer** for loading. The engine's technical specifications are listed in Table.

Initially, the engine ran with neat diesel fuel to establish basic performance, combustion, and emission characteristics. Subsequently, the engine was fueled with a **B20 blend of Cottonseed Methyl Ester (CSME)**, and then

with **CSME B20 combined with hydrogen inducted at two different flow rates (4 L/min and 8 L/min)** through the intake manifold.

The hydrogen gas was stored in a **high-pressure cylinder (up to 280 bar)** and delivered via a **double-stage diffusion pressure regulator**.

The regulated hydrogen passed through a **flame trap (water-sealed), flashback arrestor, and rotameter** before being introduced into the intake manifold at a distance of 40 mm from the valve, ensuring safe premixing with air prior to combustion. This manifold induction technique enabled hydrogen to mix uniformly with the incoming air and the injected liquid fuel.

Parameter	Specification
Make and Model	Kirloskar TV1 Type
No. of cylinders	One
Stroke	Four
Bore × Stroke	87.5 mm × 110 mm
Swept volume	661 cc
Compression ratio	14–19
Rated power	5.2 kW at 1500 rpm
Rated speed	1500 rpm
Injection timing	23° CA bTDC

Instrumentation:

The test rig was comprehensively instrumented for real-time data acquisition and analysis:

- **Eddy Current Dynamometer** (Technomech TMEC-10, 7.5 kW, 1500–6000 rpm): Coupled to the engine via a universal propeller shaft, used to apply and control load.
- **Load Cell and Torque Sensor** (Sensotronics Sanmar 6000): Measured engine torque for brake power estimation.
- **Combustion Analyzer** (National Instruments USB-6210 DAQ system): Recorded cylinder pressure and

crank-angle data at high resolution, interfaced with AVL 615 Indimeter software for pressure–crank angle, heat release rate, and mass burn fraction analysis.

- **Pressure Transducer** (PCB Piezotronics HSM111A22, 5000 psi): Piezoelectric sensor mounted flush with the combustion chamber to capture in-cylinder pressure variations.
- **Charge Amplifier** (AVL 3066A02): Converted electrical charge from the pressure transducer to voltage signals.
- **Crank Angle Encoder** (Kubler 3700, 37 mm): Provided precise crank-angle reference for combustion analysis.
- **Air and Fuel Flow Meters** (WIKA SL-1-A-MQA and Yokogawa EJA110): Measured intake air and fuel flow rates respectively.
- **Exhaust Gas Analyzer** (AVL Digas 444): Measured NO_x, HC, CO, CO₂, and O₂ concentrations using the non-dispersive infrared (NDIR) method.
- **Smoke Meter** (AVL 437C): Determined soot density and filter smoke number using the filter paper method.
- **Exhaust Gas Thermocouple (EGT)**: Measured exhaust gas temperature at the manifold outlet.

Experimental Procedure:

Before testing, the engine was allowed to run on the selected fuel for **10–20 minutes at no load** to attain steady-state conditions at a constant rated speed of **1500 rpm**. Experiments were conducted at various load conditions (0–100%) using the following standardized procedure:

1. Ensure adequate cooling water circulation and switch on all indicator systems (speed, load, temperature).
2. Start the engine by cranking at no-load condition and warm up for 10–20 minutes to reach steady-state.
3. Gradually apply load using the eddy current dynamometer's control knob.
4. Measure **fuel consumption** using a burette and stopwatch.
5. Record **speed and torque** data from the dynamometer control panel.
6. Measure **exhaust gas temperature (EGT)** using a thermocouple sensor.
7. Record **smoke opacity** using the AVL 437C smoke meter.
8. Measure **NO_x, HC, CO, CO₂, and O₂** levels using the AVL Digas 444 exhaust gas analyzer.
9. Acquire **in-cylinder pressure and TDC signals** using the pressure transducer and encoder interfaced

with the NI DAQ system and AVL Indimeter software.

10. Repeat the above procedure for:
 - Diesel (baseline)
 - B20 CSME blend
 - B20 CSME + 4 L/min hydrogen
 - B20 CSME + 8 L/min hydrogen

Each test point was repeated thrice to ensure data repeatability, and the results were averaged to minimize random errors.

VI. RESULTS & DISCUSSION

This section presents and discusses the experimental outcomes from the single-cylinder, four-stroke, water-cooled, direct-injection diesel engine operated on neat diesel, B20 Cottonseed Methyl Ester (CSME), and B20 CSME blended with hydrogen at two flow rates (4 L/min and 8 L/min). The performance, emission, and combustion characteristics were analyzed under varying engine loads from 0 % to 100 % and compared against baseline diesel operation.

Performance Characteristics:

Brake-Specific Fuel Consumption (BSFC):

BSFC is the mass of fuel consumed per unit brake power per hour (kg/kWh). A clear reduction in BSFC was observed with the introduction of hydrogen, particularly at higher loads.

At full load, the BSFC was:

- Diesel: 0.24 kg/kWh
- B20 + 4 L/min H₂: 0.25 kg/kWh
- B20 + 8 L/min H₂: 0.24 kg/kWh

Hydrogen's high flame velocity and diffusivity enhanced air–fuel premixing, leading to more complete combustion and lower fuel consumption. Its high calorific value also reduced the fuel mass flow requirement. The BSFC decreased more rapidly as load increased, and the 8 L/min hydrogen enrichment achieved about **7.7 % lower BSFC** than diesel at full load.

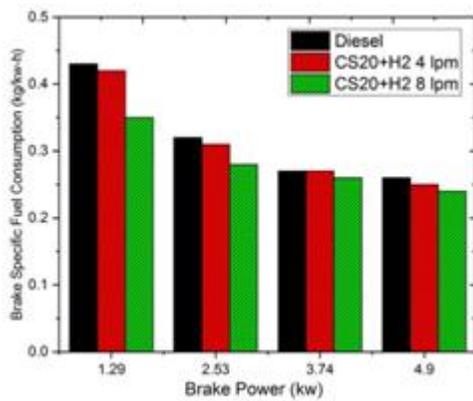


Fig. Variation of brake-specific fuel consumption with brake power

Brake Thermal Efficiency(BTE):

BTE increased steadily with increasing load for all fuels, with a steeper rise observed when hydrogen was introduced.

At full load, the BTE values were:

- Diesel: 33.35 %
- B20 + 4 L/min H₂: 33.7 %
- B20 + 8 L/min H₂: 35.5 %

The high laminar flame speed and shorter ignition delay of hydrogen contributed to faster and more complete combustion, improving thermal efficiency. The enhanced premixing also raised cylinder pressures and energy conversion efficiency. Slightly higher combustion noise was noted during dual-fuel operation, attributed to the rapid combustion of the fuel–hydrogen mixture.

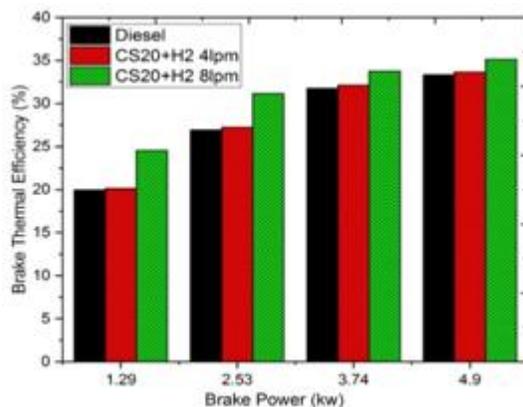


Fig. Variation of brake thermal efficiency with brake power

Emission Characteristics:

Emission characteristics were measured using an AVL Digas 444 N gas analyzer and an AVL 437C smoke meter. The key pollutants analyzed include smoke opacity, unburned hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x).

SmokeOpacity:

Smoke opacity is an indicator of particulate matter from incomplete combustion.

- Diesel: 19.8 – 62.3 %
- B20 + 4 L/min H₂: 24.4 – 66.9 %
- B20 + 8 L/min H₂: 23.1 – 61.7 %

Hydrogen enrichment reduced smoke emissions, especially at high loads. Its carbon-free structure and high flame speed promoted cleaner combustion and less soot formation, with 8 L/min hydrogen showing the lowest smoke values at peak load.

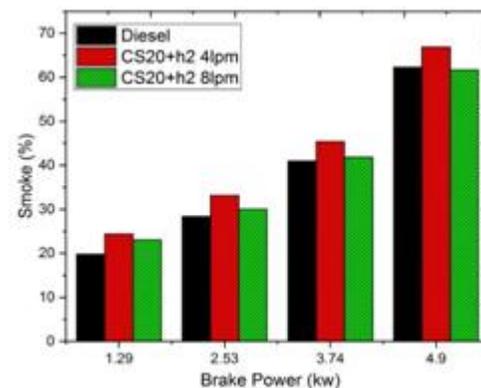


Fig. Variation of smoke opacity with brake power

Hydrocarbon (HC) Emissions:

HC emissions decreased significantly with hydrogen addition.

- Diesel: 38 – 61 ppm
- B20 + 4 L/min H₂: 48 – 68 ppm
- B20 + 8 L/min H₂: 41 – 63 ppm

Although B20 alone showed slightly higher HC than diesel at low loads, the addition of hydrogen lowered HC, especially at 8 L/min. The oxygen-rich nature of both biodiesel and hydrogen promotes more complete combustion, reducing unburned fuel. Higher cylinder temperatures from hydrogen further oxidized carbon residues, lowering HC levels.

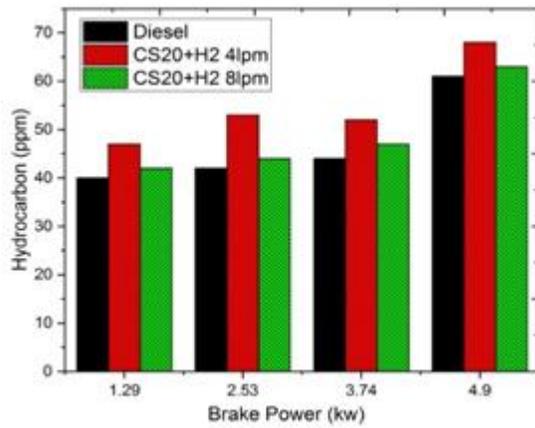


Fig. Variation of hydrocarbon emissions with brake power

Carbon Monoxide (CO) Emissions:

CO emissions dropped consistently with hydrogen enrichment.

- Diesel: 0.066 – 0.024 %
- B20 + 4 L/min H₂: 0.034 – 0.020 %
- B20 + 8 L/min H₂: 0.048 – 0.019 %

At full load, 8 L/min hydrogen yielded the lowest CO (0.019 %). The absence of carbon in hydrogen and the oxygen content in biodiesel enable more complete oxidation, suppressing CO formation. This confirms the synergistic combustion improvement with dual fueling.

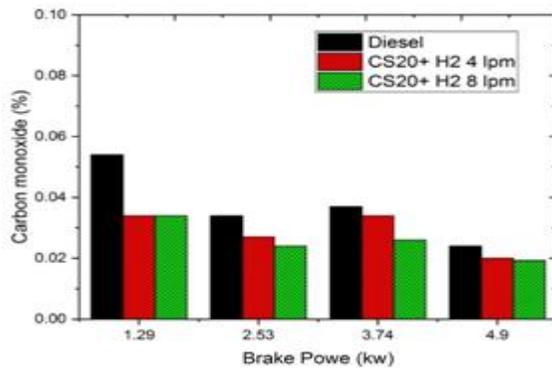


Fig. Variation of carbon monoxide emissions with brake power

Oxides of Nitrogen (NO_x) Emissions:

NO_x emissions rose with load and were slightly higher for hydrogen-enriched fuels.

- Diesel: 473 – 1902 ppm
- B20 + 4 L/min H₂: 482 – 2041 ppm
- B20 + 8 L/min H₂: 460 – 2120 ppm

The higher in-cylinder temperatures and excess oxygen from biodiesel promote thermal NO_x formation. While hydrogen improves combustion, the higher peak temperatures lead to elevated NO_x, a known trade-off in dual-fuel operation.

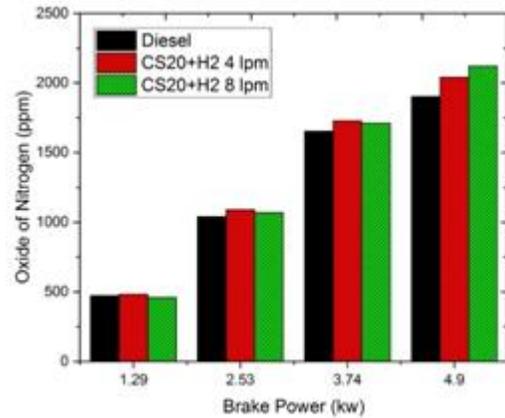


Fig. Variation of oxides of nitrogen with brake power

Combustion Characteristics:

Combustion analysis using in-cylinder pressure and crank-angle data revealed key differences in ignition delay and heat release patterns when hydrogen was introduced.

In-Cylinder Pressure

- Diesel: 67.7 bar at 12° aTDC
- B20 + 4 L/min H₂: 69.29 bar at 12° aTDC
- B20 + 8 L/min H₂: 43.56 bar at 11° aTDC

Hydrogen addition caused earlier occurrence of peak pressure due to shorter ignition delay and faster premixed combustion. The 4 L/min hydrogen blend achieved slightly higher peak pressure than diesel, while 8 L/min showed lower pressure, likely due to mixture inhomogeneity and rapid combustion leading to energy losses.

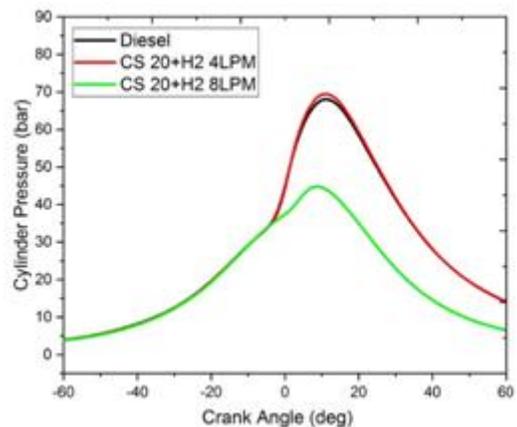


Fig. Variation of cylinder pressure with crank angle

Heat Release Rate (HRR):

- Diesel: 52 J/°CA
- B20 + 4 L/min H₂: 30.77 J/°CA
- B20 + 8 L/min H₂: 15.18 J/°CA

Hydrogen enrichment advanced the start of combustion and shortened ignition delay. Its high flame propagation speed generated turbulence and improved premixing. Although peak HRR of biodiesel blends was lower, the earlier heat release with hydrogen shows faster energy liberation, aligning with the observed efficiency gains. Rapid hydrogen combustion increased turbulence and reduced delay time, causing higher pressure rise rates at elevated loads.

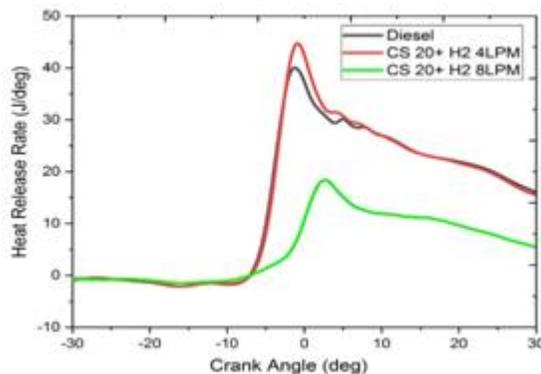


Fig. Variation of heat release rate with crank angle

Summary of Key Findings:

- Brake thermal efficiency improved with hydrogen, with 8 L/min showing the highest value (35.5 %).
- BSFC decreased by about 7–8 % at full load compared to diesel.
- Smoke, CO, and HC emissions were significantly lower due to cleaner combustion.
- NO_x emissions increased slightly due to higher peak combustion temperatures.
- Hydrogen enabled faster combustion with shorter ignition delay and advanced heat release.

These results confirm that dual fueling with cottonseed methyl ester and hydrogen can enhance engine efficiency and reduce most exhaust emissions, while offering a sustainable alternative for compression ignition engines.

VII. CONCLUSION & FUTURE SCOPE

This study investigates the performance and emission characteristics of a single-cylinder, four-stroke, air-cooled

Variable Compression Ratio (VCR) Direct Injection (DI) diesel engine fueled with a 20% methyl ester of cottonseed oil blend, enriched with hydrogen at flow rates of 4 and 8 liters per minute (lpm). The results are compared with conventional diesel fuel to assess the impact of hydrogen enrichment on engine efficiency and emissions.

Performance Analysis:

- **Brake Thermal Efficiency (BTE):** The BTE with diesel fuel was 33.35%, which increased to 33.65% and 35.12% with 4 lpm and 8 lpm hydrogen enrichment, respectively, at full load. The high flame velocity of hydrogen facilitated better mixing of the methyl ester blend with air, leading to improved thermal efficiency.
- **Brake Specific Fuel Consumption (BSFC):** BSFC decreased with increasing hydrogen enrichment. At full load, BSFC values were 0.25 kg/kWh for diesel, and 0.24 kg/kWh for both 4 lpm and 8 lpm hydrogen-enriched blends. This reduction is attributed to the enhanced combustion efficiency from hydrogen addition.

Emission Characteristics:

- **Nitrogen Oxides (NO_x):** NO_x emissions ranged from 473 to 1902 ppm with diesel fuel. With 4 lpm and 8 lpm hydrogen enrichment, NO_x concentrations increased to 482–2041 ppm and 460–2120 ppm, respectively. The rise in NO_x is due to higher in-cylinder temperatures facilitated by hydrogen combustion.
- **Smoke Opacity:** Smoke opacity decreased with hydrogen enrichment. At full load, smoke opacity was 66.9% with 4 lpm and 61.7% with 8 lpm hydrogen enrichment, indicating more complete combustion.
- **Hydrocarbons (HC):** HC emissions were lower with diesel fuel (38–61 ppm). With 4 lpm and 8 lpm hydrogen enrichment, HC emissions increased to 40–68 ppm and 39–63 ppm, respectively. The increase is due to the absence of carbon in hydrogen, which reduces combustion temperature and increases HC emissions.
- **Carbon Monoxide (CO):** CO emissions decreased with hydrogen enrichment. At full load, CO levels were 0.024% with diesel, 0.02% with 4 lpm, and 0.019% with 8 lpm hydrogen enrichment, reflecting improved combustion efficiency.

Combustion Characteristics:

- **Peak Pressure:** The peak pressure was 67.94 bar with diesel fuel. With 4 lpm and 8 lpm hydrogen enrichment, peak pressures decreased to 69.29 bar and 43.51 bar, respectively. The reduction in peak pressure is due to the rapid combustion of hydrogen, leading to smoother pressure profiles.

Overall, the 20% cottonseed biodiesel blend with 8 lpm hydrogen enrichment exhibited the best performance at full load, demonstrating its potential as an effective fuel for compression ignition engines.

Future Scope:

- **Alternative Biodiesel Sources:** Further research into the impacts of other types of biodiesel, such as those derived from algae or waste oils, on engine efficiency and emission profiles when used in conjunction with hydrogen enrichment is recommended.
- **Emission Reduction Strategies:** Investigating the use of high-octane alcohols or nanoparticle additives to mitigate the increase in NO_x emissions associated with hydrogen enrichment could be beneficial.
- **Engine Parameter Optimization:** Studies focusing on optimizing engine parameters, including compression ratio, fuel injection timing, and fuel injection pressure, can further enhance the performance and emission characteristics of hydrogen-enriched biodiesel blends.

VIII. ACKNOWLEDGEMENT

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REFERENCES

- [1] Aydin, H. (2010). Performance and emission analysis of cottonseed oil methyl ester in a diesel engine. *Renewable Energy*, 35(3), 588–592.
- [2] Nachippan, N. M., & Senthilkumar, P. (2025). Performance and emission analysis of cotton seed oil methyl ester with hydrogen enrichment in a diesel engine. *Fuel Communications*, 16, 100805.

- [3] Tosun, E. (2021). Hydrogen enrichment effects on performance and emission characteristics of a diesel engine operated with diesel-soybean biodiesel blends with nanoparticle addition. *Fuel*, 287, 119483.
- [4] Sonkar, N., Sharma, A., & Pandey, R. K. (2023). A review of performance and emission parameters of hydrogen-enriched biodiesel in diesel engines. *AIP Conference Proceedings*, 2745(1), 030010.
- [5] Gurusamy, M., Kumaravel, A., & Rajesh, M. (2023). Experimental evaluation of cottonseed oil–camphor binary blend in a diesel engine. *Biofuels*, 14(7), 713–724.

APPENDIX

Performance Correlations:

The mathematical correlations which were used to compute the performance characteristics of the research engine were included below.

Brake Power:

$$BP \text{ (kW)} = \frac{2\pi NT}{60000}$$

Where, N – No. of revolution, rpm, T- Torque, N-m

Brake Thermal Efficiency:

$$BTE \text{ (\%)} = \frac{B.P \times 100}{TFC \times C.V}$$

Where, B.P- Brake power, kW

TFC- Total fuel consumption, kg/sec

C.V- Calorific value, kJ/kg

Brake Specific Fuel Consumption:

$$BSFC \left(\frac{\text{kg}}{\text{kWhr}} \right) = \frac{TFC}{BP}$$

Where, TFC- Total Fuel Consumption, kg/hr

B.P- Brake power, kW

Brake Specific Energy Consumption:

$$BSEC \left(\frac{\text{kJ}}{\text{kWhr}} \right) = BSFC * CV$$

Where, C.V- Calorific value, kJ/kg.



Fig. Port Injected Hydrogen Fuel



Fig. Experimental Engine Setup