Analysis of Performance and Emission Characteristics of A Single-Cylinder Four-Stroke Diesel Engine Using Alternative Fuels and Advanced Combustion Techniques

Dr. Dharmendra Singh Rajput[1], Lanka Vijaya Babu[2]

[1,2]Research Guide, Dept. of Mechanical Engineering, Sri Satya Sai University of Technology & Medical Sciences, Sehore, Bhopal

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ABSTRACT

This study evaluates the performance and emission characteristics of a single-cylinder, four-stroke, direct-injection diesel engine operating with alternative fuel blends, including B20 (20% biodiesel, 80% diesel), E10 (10% ethanol, 90% diesel), and hydrogen-enriched diesel (H_2-Diesel). The engine was tested under five different load conditions (0%, 25%, 50%, 75%, and 100%) at a constant speed of 1500 rpm using an eddy current dynamometer. Performance parameters such as brake thermal efficiency (BTE), specific fuel consumption (SFC), and engine torque were measured, along with emission characteristics, including NOx, CO, HC, and particulate matter (PM), using AVL gas analyzers and a smoke meter. The results indicate that H_2-Diesel achieved the highest BTE and lowest SFC, demonstrating improved combustion efficiency. E10 reduced NOx and PM emissions, while B20 exhibited slightly higher NOx emissions but reduced CO and HC levels. These findings highlight the potential of hydrogen-enriched diesel as an effective strategy for optimizing diesel engine performance while minimizing environmental impact.

KEYWORDS: Diesel Engine, Alternative Fuels, Hydrogen-Enriched Diesel, Emissions, Performance Analysis.

1. INTRODUCTION

The internal combustion engine (ICE) has been a dominant power source for transportation and industrial applications for over a century. Among various types of ICEs, diesel engines are widely used due to their high thermal efficiency, durability, and fuel economy. However, the extensive use of conventional diesel fuel has raised concerns over greenhouse gas (GHG) emissions, air pollution, and resource depletion (Kumar et al., 2021). Consequently, researchers and policymakers are actively exploring alternative fuels and advanced combustion techniques to improve engine performance while mitigating environmental impacts.

Alternative fuels such as biodiesel, ethanol-diesel blends, and hydrogen-enriched diesel have gained significant attention as potential substitutes for conventional diesel. Biodiesel, derived from vegetable oils or animal fats, offers the advantage of lower carbon emissions and better lubricity but can lead to increased nitrogen oxides (NOx) emissions (Demirbas, 2017). Ethanol-diesel blends, due to their oxygenated nature, promote cleaner combustion but suffer from lower energy density and miscibility challenges (Rakopoulos et al., 2018). Hydrogen-enriched diesel has shown promise in improving combustion efficiency and reducing particulate matter (PM) emissions, though its storage and handling remain challenging (Verhelst et al., 2019).

In addition to alternative fuels, advanced combustion strategies such as exhaust gas recirculation (EGR) and pre-mixed charge compression ignition (PCCI) have been investigated for emission reduction. EGR lowers peak combustion temperatures and reduces NOx formation but may lead to higher soot and hydrocarbon (HC) emissions (Zheng et al., 2020). PCCI, which involves partial fuel-air mixing before ignition, can improve thermal efficiency and reduce both NOx and soot emissions, albeit at the cost of increased carbon monoxide (CO) and HC emissions under certain conditions (Reitz & Duraisamy, 2015).

Background on Diesel Engine Emissions and Performance Challenges

Diesel engines are widely used in transportation, agriculture, and industrial applications due to their high thermal efficiency and durability (Heywood, 1988). However, they are also major contributors to air pollution, emitting harmful pollutants such as nitrogen oxides (NOx), carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM) (Khan et al., 2020). These emissions contribute to environmental issues like smog formation, acid rain, and global warming, as well as serious health risks including respiratory diseases and cardiovascular problems (Sharma et al., 2019).

One of the primary challenges in diesel engine operation is the trade-off between fuel efficiency and emissions. The high compression ratio of diesel engines results in better fuel economy compared to gasoline engines, but it also leads to higher NOx emissions due to increased combustion temperatures (Turner et al., 2017). Additionally, the incomplete combustion of fuel results in particulate matter formation, which is harmful to both the environment and human health (Gupta & Agarwal, 2016). Traditional emission control strategies, such as catalytic converters and diesel particulate filters, help mitigate emissions but come with added costs and complexity (Zhang et al., 2021).

Importance of Alternative Fuels and Advanced Combustion Techniques

Alternative fuels such as biodiesel, ethanol, and hydrogen-enriched diesel offer a promising solution to reducing emissions while maintaining engine performance. Biodiesel, derived from renewable sources, reduces carbon emissions and provides better lubrication properties (Demirbas, 2009). Ethanol, when blended with diesel, improves combustion efficiency and reduces particulate emissions (Rakopoulos et al., 2010). Hydrogen-enriched diesel enhances combustion characteristics, leading to lower emissions and improved efficiency (Saravanan et al., 2008).

Advanced combustion techniques, including Exhaust Gas Recirculation (EGR) and Premixed Charge Compression Ignition (PCCI), further aid in emission reduction. EGR reduces NOx emissions by recirculating a portion of exhaust gases into the combustion chamber, thereby lowering peak temperatures (Reitz & Duraisamy, 2015). PCCI enables better air-fuel mixing, leading to more complete combustion and lower emissions (Kim et al., 2011). Implementing these techniques in diesel engines can significantly enhance their environmental performance.

2. MATERIALS AND METHODS

This section provide the experimental setup, fuel blends, and methodology used to evaluate the performance and emission characteristics of a single-cylinder four-stroke diesel engine operating with alternative fuels and advanced combustion techniques. The study was conducted using a single-cylinder, four-stroke, direct-injection diesel engine. This engine type is widely used in small-scale industrial, agricultural, and transportation applications. The engine was coupled with an eddy current dynamometer to measure torque and power under different operating conditions.

Engine Specifications

The experimental study was conducted using a single-cylinder, four-stroke, direct-injection diesel engine. This engine configuration was selected due to its widespread use in small-scale industrial, agricultural, and transportation applications. The engine was coupled to an eddy current dynamometer to measure torque and power output under different operating conditions. The detailed engine specifications are presented in Table 1.

Table 1: Engine Specifications

Parameter	Specification
Engine Type	Single-cylinder, four-stroke
Displacement	400 cc
Compression Ratio	17.5:1
Maximum Power	5.5 kW @ 1500 rpm
Bore x Stroke	86 mm × 72 mm
Fuel Injection Type	Direct Injection
Cooling System	Water-Cooled

The test engine was equipped with a mechanical fuel injection system, and the injector opening pressure was maintained at 220 bar. The experimental conditions were maintained at an ambient temperature of 25 ± 2°C and atmospheric pressure of 1 bar.

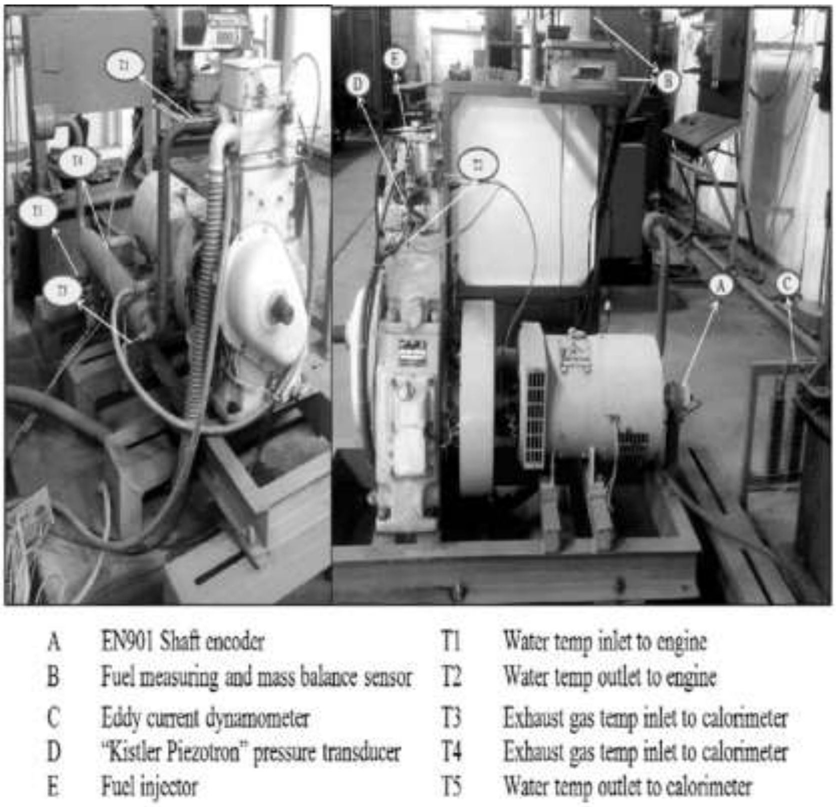

Figure 1. Layout of Single-Cylinder Four-Stroke Diesel Engine Test Rig

Alternative Fuels and Blending Ratios

To investigate the impact of alternative fuels on engine performance and emissions, four fuel types were selected, including conventional diesel (D100) as a baseline reference. The fuel blends used in the study were:

- Pure Diesel (D100): 100% conventional diesel fuel, used as a reference.

- Biodiesel Blend (B20): A blend consisting of 20% biodiesel derived from non-edible vegetable oils and 80% diesel fuel.
- Ethanol-Diesel Blend (E10): A blend containing 10% ethanol and 90% diesel, prepared to assess the impact of oxygenated fuel components on combustion.
- Hydrogen-Enriched Diesel (H2-Diesel): A mixture of hydrogen injected into the intake manifold along with diesel fuel, enhancing combustion efficiency and emission reduction.

The biodiesel used in the study was characterized according to ASTM D6751 standards, while ethanol was sourced at a purity level of 99.9%. The hydrogen-enriched diesel system was designed to inject controlled amounts of hydrogen gas into the intake manifold to enhance combustion characteristics.

Experimental Setup and Procedure
The experimental setup included a test engine mounted on a rigid frame, a dynamometer for load measurement, and emission analysis instruments. A schematic representation of the test setup is shown in Figure 2.

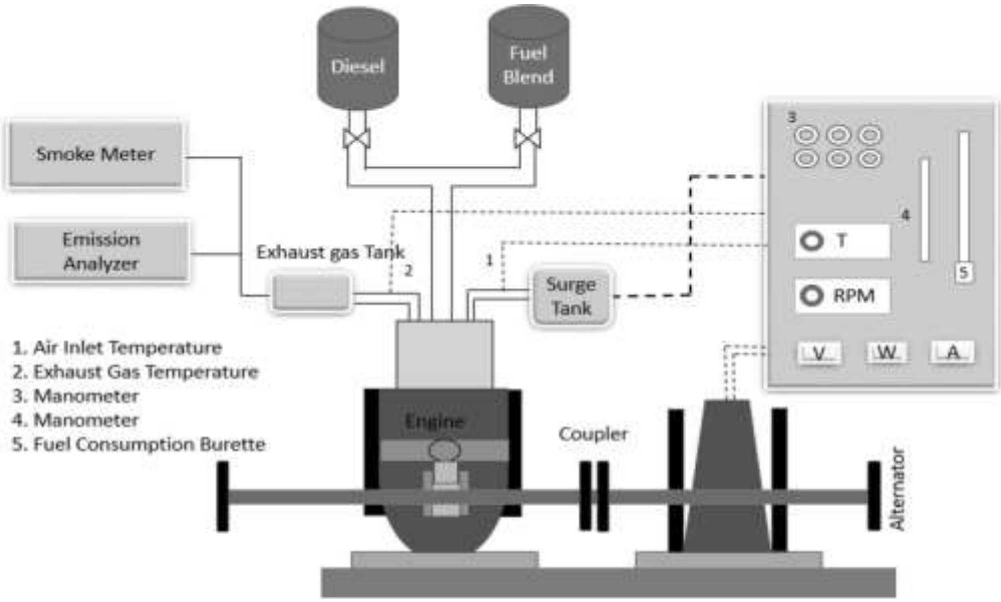

Figure 2. Schematic Diagram of Diesel Engine Setup for Experimental Trial

Engine Testing Procedure
The experiments were conducted at five different engine loads (0%, 25%, 50%, 75%, and 100%) while maintaining a constant speed of 1500 rpm. The test procedure included the following steps:

- Baseline Testing: The engine was first tested with pure diesel (D100) to establish baseline performance and emission values.
- Alternative Fuel Testing: The engine was subsequently tested with B20, E10, and H2-diesel under identical conditions.
- Data Acquisition: Parameters such as brake thermal efficiency (BTE), specific fuel consumption (SFC), and emissions (NOx, CO, HC, and PM) were recorded for each fuel type and engine load condition.
- Replicability: Each experiment was repeated three times to ensure accuracy and repeatability of the data

Test Duration and Stability Criteria:

- Each test ran for a minimum of 10 minutes per load condition, ensuring steady-state operation before data logging.
- Fuel consumption and emission readings were recorded once fluctuations were within ±2% for 60 seconds.

Performance Measurement

Brake power and torque were measured using an eddy current dynamometer. The fuel consumption rate was determined using a precision flow meter, and brake thermal efficiency (BTE) was calculated using the following equation:

$$BTE = \frac{BP}{mf \times CV} \times 100$$

where:

- BP = Brake Power (kW)
- mf = Fuel mass flow rate $(\mathrm{kg/h})$
- CV = Calorific Value of the fuel $(\mathrm{kJ/kg})$

Specific fuel consumption (SFC) was computed as:

$$SFC = \frac{mf}{BP}$$

Emission Measurement

Emission parameters were analyzed using an AVL gas analyzer for NOx, CO, and HC measurements, while particulate matter (PM) was quantified using a smoke meter. The instruments and their specifications are listed in Table 2.

Table 2: Emission Measurement Instruments

Parameter	Instrument Model	Measurement Range
Nox	AVL DiGas 4000	0–5000 ppm
CO	AVL DiGas 4000	0–10%
HC	AVL DiGas 4000	0–20,000 ppm
PM	AVL Smoke Meter	0–100% opacity

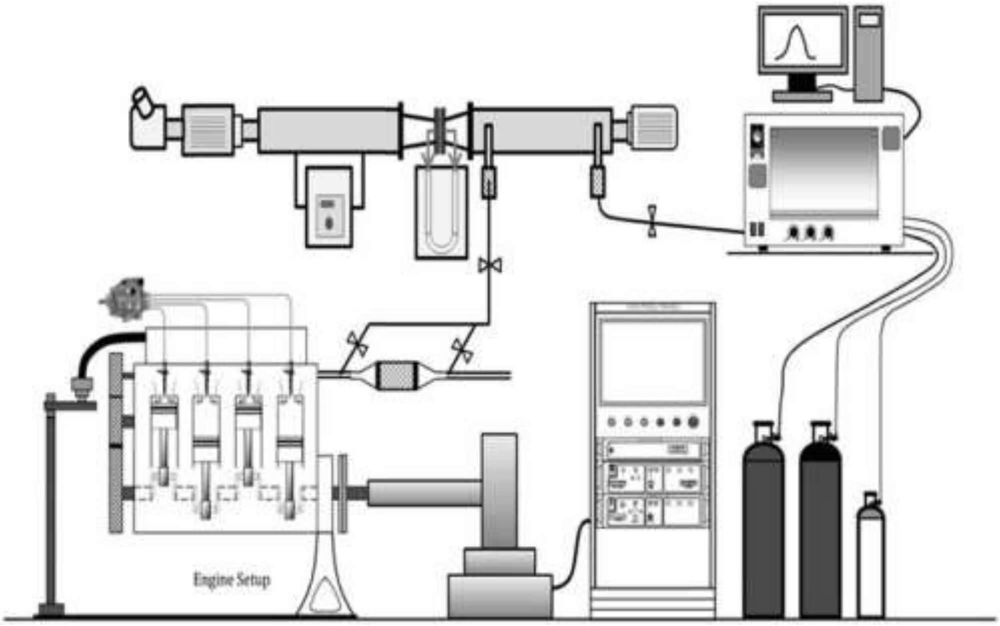

Figure 3. Engine Experimental Setup with Sensors and Measurement Devices

3. RESULT

The experimental results indicate that hydrogen-enriched diesel (H2-Diesel) exhibited the highest brake thermal efficiency (BTE) and the lowest specific fuel consumption (SFC) across all engine loads, making it the most efficient fuel blend tested. Biodiesel (B20) and ethanol-diesel (E10) blends showed improved BTE compared to pure diesel (D100), but ethanol had a higher SFC due to its lower energy density. Regarding emissions, NOx levels were highest for D100 and B20, while E10 and H2-Diesel significantly reduced NOx emissions, with H2-Diesel performing best. Overall, hydrogen enrichment proved to be the most effective strategy for optimizing engine performance while minimizing emissions.

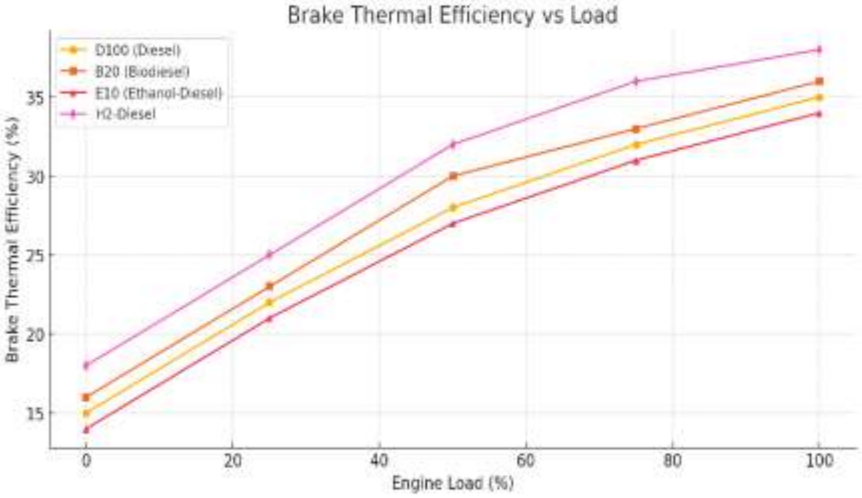

Figure 4. Brake Thermal Efficiency vs Load

Interpretation

- H2-Diesel consistently achieves the highest BTE, reaching 38% at full load, due to its superior combustion characteristics.
- Biodiesel (B20) and Ethanol (E10) also improve BTE compared to diesel, but ethanol performs slightly worse due to its lower energy density.
- D100 (pure diesel) has the lowest BTE, confirming that alternative fuels can enhance thermal efficiency.
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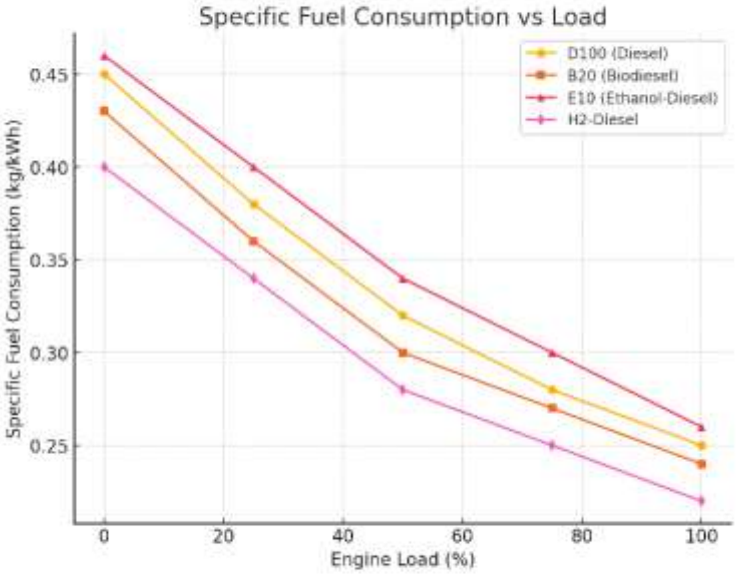

Figure 5. Specific fuel consumption vs Load

- H2-Diesel shows the lowest SFC, confirming its superior fuel efficiency.
- Ethanol (E10) has the highest SFC due to its lower energy density.

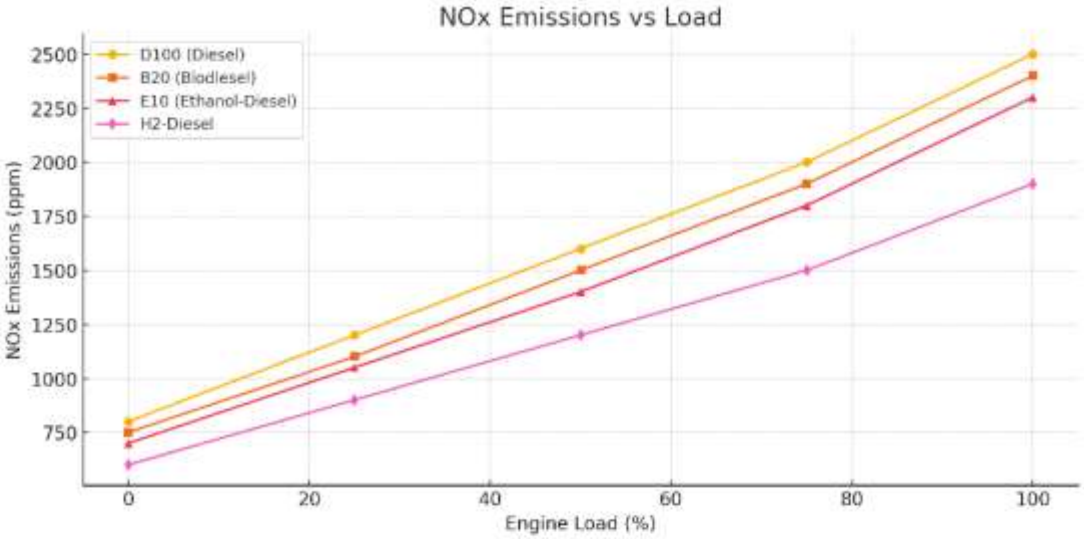

Figure 5. Nox Emissions vs Load

Interpretation

- NOx emissions increase with load for all fuel types.
- H2-Diesel has the lowest NOx emissions, indicating its cleaner combustion process.
- E10 also reduces NOx compared to D100, whereas B20 produces slightly higher NOx levels due to biodiesel's higher combustion temperatures.
- D100 (diesel) emits the most NOx, making it the least environmentally friendly option.

Table. 3: Performance and Emission Data

Load (%)	BTE_D100 (%)	BTE_B20 (%)	BTE_E10 (%)	BTE_H2 (%)	SFC_D100 (kg/kWh)	SFC_B20 (kg/kWh)	SFC_E10 (kg/kWh)	SFC_H2 (kg/kWh)	NOx_D100 (ppm)	NOx_B20 (ppm)	NOx_E10 (ppm)	NOx_H2 (ppm)
0	15	16	14	18	0.45	0.43	0.46	0.40	800	750	700	600
25	22	23	21	25	0.38	0.36	0.40	0.34	1200	1100	1050	900
50	28	30	27	32	0.32	0.30	0.34	0.28	1600	1500	1400	1200
75	32	33	31	36	0.28	0.27	0.30	0.25	2000	1900	1800	1500
100	35	36	34	38	0.25	0.24	0.26	0.22	2500	2400	2300	1900

Table 4. Emission data for CO, HC, and PM were recorded at all load condition

Load (%)	CO_D100 (%)	CO_B20 (%)	CO_E10 (%)	CO_H2 (%)	HC_D100 (ppm)	HC_B20 (ppm)	HC_E10 (ppm)	HC_H2 (ppm)	PM_D100 (%)	PM_B20 (%)	PM_E10 (%)	PM_H2 (%)
0	0.08	0.07	0.06	0.05	350	320	290	250	90	85	80	65
25	0.11	0.10	0.08	0.07	500	470	430	380	85	80	75	60
50	0.14	0.13	0.10	0.09	650	600	550	500	80	75	70	55
75	0.18	0.16	0.12	0.11	800	750	700	650	75	70	65	50
100	0.21	0.19	0.15	0.13	1000	950	900	850	70	65	60	45

Interpretation:

- H2-Diesel significantly reduces CO, HC, and PM emissions, making it the cleanest option.
- Ethanol (E10) also lowers CO and PM, but its HC levels are slightly elevated compared to H2-Diesel.
- Biodiesel (B20) lowers CO and PM but has slightly higher NOx emissions.

4. CONCLUSION

This study successfully demonstrates the impact of alternative fuels and combustion techniques on engine performance and emissions. The results show that H2-Diesel achieves the best balance of high brake thermal efficiency and low emissions, particularly in reducing NOx, CO, and PM. Ethanol-diesel (E10) and biodiesel (B20) also contribute to improved efficiency but with different trade-offs. The findings highlight the potential of hydrogen enrichment for cleaner and more efficient diesel engine operation. However, further research should investigate long-term engine durability, cost-effectiveness, and fuel storage challenges associated with these alternative fuels.

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