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A systematic literature review on biodiesel–hydrogen dual-fuel engines: feedstock diversity, performance, emission and combustion characteristics

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Biodiesel–hydrogen dual-fuel technology has emerged as a promising approach to improve the performance and environmental sustainability of compression ignition (CI) engines. This systematic literature review aims to evaluate the influence of hydrogen addition on biodiesel-fueled CI engines by synthesising recent studies on feedstock diversity, engine performance, emissions, and combustion characteristics. A systematic search was conducted using the Scopus database, and 34 eligible studies published between 2020 and 2025 were selected following the PRISMA guideline. The review shows that hydrogen enrichment generally improves brake thermal efficiency and reduces brake-specific fuel consumption by promoting faster, more complete combustion. Significant reductions in CO, HC, and particulate-related emissions are consistently reported, whereas NO_x emissions tend to increase because of higher in-cylinder combustion temperatures. Unlike previous reviews that mainly focus on biodiesel production or hydrogen-fuelled engines independently, this review provides an integrated assessment of biodiesel–hydrogen dual-fuel compression ignition engines by correlating biodiesel feedstock diversity with engine performance, emission characteristics, and combustion behaviour. The synthesized findings highlight the interactions between fuel properties, hydrogen addition, and engine operating parameters, providing evidence-based recommendations for optimizing biodiesel–hydrogen dual-fuel diesel engines and guiding future research.

Key words: *compression ignition, exhaust gas recirculation, injection strategy, PRISMA, Zeldovich mechanism*

1. Introduction

Climate change mitigation through energy system decarbonization has become the most urgent global mandate of this century. However, field realities show that dependence on fossil fuels remains dominant, as reflected in Fig. 1, namely, the escalation of global Greenhouse Gas (GHG) emissions to a record high of 53.2 Gt CO_2eq in 2024 [16]. In Indonesia, this challenge is amplified in the transportation sector, which has seen emissions increase by more than 300% since 1990 [16]. This historical trend contradicts the global decarbonization target under the Net Zero Emissions (NZE) scenario, which requires a drastic reduction in oil demand in the transportation sector, from around 110 EJ in 2023 to less than 25 EJ by 2050. Such a radical transformation can only be achieved through accelerated adoption of clean energy vectors such as electricity, bioenergy, and hydrogen [32]. Given that full electrification in the heavy-duty transportation sector remains constrained by technical and infrastructural barriers [3, 17, 23, 44], decarbonizing existing CI engines through the synergistic integration of bioenergy and hydrogen emerges as the most pragmatic and vital immediate transitional strategy [21, 40, 82].

Although the paradigm of electric vehicles continues to evolve, CI engines remain the backbone of heavy industry, maritime, and power generation sectors due to their superior thermal efficiency and torque density [18, 88]. In an effort to sustain these engines while reducing carbon emissions, Biodiesel (fatty acid methyl ester – FAME) has emerged as a primary alternative fuel candidate due to its renewable nature, biodegradability, and intrinsic oxygen content [30, 87].

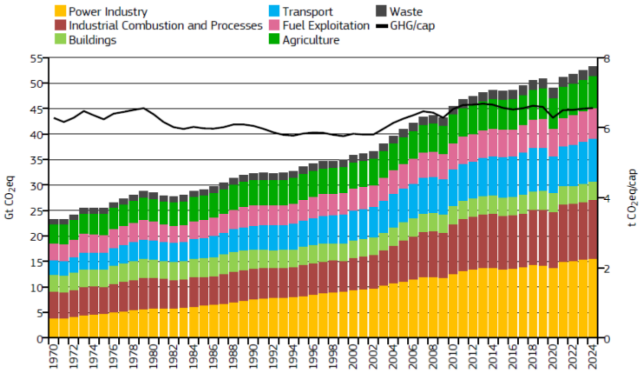

Fig. 1. Global GHG emissions by sector and per capita, 1970-2024 (in Gt CO_2eq) [16]

However, the use of pure biodiesel (B100) is constrained by fundamental physicochemical limitations. Biodiesel exhibits a kinematic viscosity that is 10 to 12 times higher than that of conventional diesel and has low volatility [10, 46, 57]. These characteristics hinder atomization in injectors, resulting in fuel droplets with larger average diameters (Sauter Mean Diameter) [25, 31]. The technical consequences of poor atomization include incomplete combustion, often manifested in reduced BTE, cold-start difficulties, and significant increases in particulate or smoke opacity emissions under certain EL [7, 8, 22, 59, 73, 81, 83].

To overcome the limitations of biodiesel combustion, the concept of hydrogen enrichment via dual-fuel mode has attracted considerable attention over the past decade [34]. Hydrogen and biodiesel possess highly contrasting yet complementary combustion characteristics [19]. Biodiesel, with its high cetane number, serves as an excellent pilot ignition source [13]. Meanwhile, hydrogen, with its high auto-ignition temperature but extreme laminar flame speed (±2.7 m/s), accelerates flame propagation within the combustion chamber [68].

This synergistic mechanism allows hydrogen flames to help "burn out" the slow-reacting biodiesel zones, thereby enhancing overall combustion efficiency [12]. Furthermore, as a carbon-free fuel, partial substitution of biodiesel energy with hydrogen theoretically reduces CO_2 emissions and drastically eliminates soot formation, making this combination highly promising for environmental sustainability [86]. Nevertheless, hydrogen addition introduces serious emission trade-offs. The rapid HRR from hydrogen combustion causes spikes in cylinder temperature and peak pressure [41]. Based on chemical kinetics, such extreme combustion temperatures trigger the Zeldovich mechanism, oxidizing atmospheric nitrogen into NO_x [2, 71]. Literature consistently reports that hydrogen enrichment is almost always accompanied by exponential increases in NO_x emissions [1, 64].

Moreover, if hydrogen flow rates are not precisely controlled, engines are prone to abnormal combustion phenomena such as knocking and backfire [37, 45, 49]. The complexity of these challenges demands more sophisticated control strategies beyond mere hydrogen dosing. The literature indicates that modifications to injection parameters, particularly SOI, play a key role in resolving this trade-off dilemma. Retarding SOI has proven effective in mitigating NO_x formation by shifting the combustion phase away from TDC, thereby lowering peak cylinder temperatures [36, 41, 58, 60]. However, implementing this strategy faces significant technical barriers, notably the absence of a universally applicable standard.

The uncertainty in optimal injection timing stems from the diversity of physicochemical properties of biodiesel feedstocks [27]. Biodiesel is not a homogeneous fuel; the viscosity, density, and cetane number profiles of palm oil-based biodiesel differ significantly from those of jatropha- or waste cooking oil-based biodiesel [6, 24, 84]. These fundamental property variations directly affect ignition delay (ID) and atomization quality when interacting with hydrogen's rapid combustion rate [11]. Consequently, an injection strategy optimal for one feedstock may reduce thermal efficiency or worsen emissions for another.

Unfortunately, the triangular interaction between feedstock diversity, injection strategy, and hydrogen performance has not been comprehensively mapped in secondary literature. Existing review papers tend to be fragmented, with most focusing either on dual-fuel engines (pure diesel + hydrogen) or on biodiesel production processes, without addressing the technical implications of their application with hydrogen [5, 72]. No comprehensive review has systematically correlated biodiesel feedstock types with appropriate operational strategies to balance NO_x emissions and engine performance. This knowledge gap hampers the development of adaptive operational guidelines for future biodiesel-hydrogen diesel engines.

Therefore, this SLR aims to fill this gap by:
- Identifying the diversity of biodiesel feedstocks used in recent studies and analyzing how hydrogen's thermal characteristics (e.g., flame speed) compensate for biodiesel's physicochemical deficiencies, particularly high viscosity and density that often hinder atomization
- Analyzing the impact of hydrogen integration on engine efficiency (BTE and BSFC), evaluating trade-offs between carbon emission reductions (CO, CO_2, PM) and NO_x increases, and synthesizing transformations of fundamental combustion parameters, cylinder pressure (CP), HRR, and ID due to altered heat release profiles
- Providing strategic recommendations for future research regarding appropriate biodiesel feedstock selection and determination of key operational factors to optimize combustion in dual-fuel biodiesel-hydrogen diesel engines.

2. Methodology

2.1. Scope of research and question formulation

This study was designed as an SLR, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [47, 51]. This protocol was selected to ensure transparency, reproducibility, and objectivity in identifying, selecting, and synthesizing the literature on dual-fuel biodiesel–hydrogen diesel engines. In general, the procedural stages of literature selection in this study, from initial identification to the final inclusion of articles, are schematically summarized in Fig. 2.

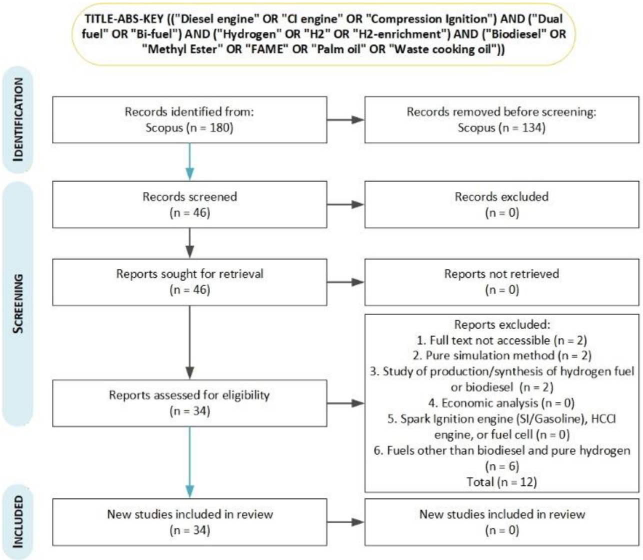

Fig. 2. PRISMA flow diagram

2.2. Scope of research and question formulation

A fundamental step in this review protocol is defining the scope of research using the PICOC framework (Population, Intervention, Comparison, Outcome, Context) [63, 76]. This framework is employed to narrow the search focus and formulate precise research questions (RQ) [15]. The details of the PICOC elements established for this study are presented in Table 1.

The study addresses three main research questions:

- RQ1: Which biodiesel feedstocks are used in biodiesel–hydrogen blends, and how do their fuel properties affect results?
- RQ2: What factors help improve combustion, performance, and emissions in dual-fuel biodiesel–hydrogen engines?
- RQ3: What future research should focus on to address challenges in dual-fuel biodiesel–hydrogen engines, especially in choosing feedstocks and factors?

Table 1. PICOC framework

Element	Definitions in This Study
Population (P)	CI engines operating on biodiesel from various feedstocks.
Intervention (I)	Implementation of a dual-fuel strategy with the addition of hydrogen (H_2).
Comparison (C)	• Comparison of fuel properties of various biodiesel feedstocks. • Comparison of factors applied in the study.
Outcome (O)	• Fuel property compatibility. • Performance (BTE, BSFC), emissions (CO, CO_2, PM, NO_x), and combustion characteristics (CP, HRR, ID). • Optimization strategies and future research directions.
Context (C)	Experimental studies or validated simulations, published in international journals (Scopus indexed, 2020–2025, open access, English).

2.3. Literature search strategy

The literature search was conducted systematically following the PRISMA 2020 guideline to ensure a transparent and reproducible article selection process. Scopus was selected as the primary database because it provides broad coverage of peer-reviewed publications in energy, combustion, and mechanical engineering, particularly studies on alternative fuels and internal combustion engines.

The search focused on studies investigating biodiesel–hydrogen dual-fuel operation in compression ignition (CI) engines, last accessed on December 6, 2025. Relevant publications were identified using combinations of keywords and Boolean operators associated with biodiesel feedstocks, hydrogen enrichment, combustion characteristics, engine performance, and exhaust emissions. The complete search string used in this review is presented in Fig. 2.

To improve the relevance and consistency of the retrieved literature, automatic filtering was applied based on publication year (2020–2025), document type, language, and open-access availability. The resulting records were subsequently subjected to the screening and eligibility assessment process described in the following subsection.

2.4. Study screening and eligibility assessment

Following the literature search, the retrieved records underwent structured screening and eligibility assessment in accordance with the PRISMA 2020 guidelines to ensure that only studies directly relevant to biodiesel–hydrogen dual-fuel combustion in compression ignition (CI) engines were included in the review.

The screened articles were evaluated through full-text assessment using the predefined inclusion and exclusion criteria presented in Table 3. Each study was examined for relevance to the research scope, including engine type, fuel combination, experimental validation, and availability of quantitative data on engine performance, emissions, and combustion characteristics.

Following this assessment, 12 studies were excluded because they did not satisfy the eligibility criteria. Consequently, 34 studies met all selection requirements and were included in the final qualitative synthesis. A summary of the screening process is presented in Table 2, while the overall workflow is illustrated in the PRISMA flow diagram shown in Fig. 2.

Table 2. Summary of article screening and selection process based on the PRISMA protocol

Selection stage	Number of articles
Initial records identified	180
Records after automatic filters	46
Excluded after full-text eligibility assessment	12
Final included studies	34

2.5. Eligibility criteria (inclusion and exclusion)

After the initial Scopus search yielded 180 articles, the studies were filtered automatically and manually based on the inclusion and exclusion criteria presented in Table 3. The screening results are presented in Fig. 2.

Table 3. Summary of article screening and selection process based on the PRISMA protocol

Filtering method	Category	Inclusion criteria	Exclusion criteria
Automatic filtering	Document Type & source	Research articles published in journals.	Review articles, conference proceedings, book chapters, and editorials.
	Publication status	Final. Complete published articles with fixed volume, issue, and page numbers.	Articles in press (articles still under editing/not yet assigned page numbers).
	Accessibility	Open Access to ensure transparency and availability of full-text data.	Subscription/paywalled articles that restrict public access to the data.
	Publication period	2020–2025 (last 6 years).	Published before 2020 and after 2025.
	Language	English.	Non-English languages.
Manual filtering (full-text eligibility assessment)	Engine Subject	CI engine	Spark ignition engines, HCCI engines, or fuel cells.
	Fuel	Using a combination of biodiesel (from various feedstocks) and hydrogen.	Fuels other than biodiesel (pure diesel, ammonia, ethanol, gasoline, Oxyhdrogen Gas/HHO, biodiesel+CNG).
	Research method	Experimental studies (Top Priority) or validated simulations.	Pure numerical simulation studies without validation.
	Data focus	Data related to biodiesel fuel properties, injection strategies, combustion results, performance, and engine emissions.	Fuel production/synthesis studies or economic analyses.

3. Result

3.1. Biodiesel fuel used in experimental research

This section synthesizes findings from 34 PRISMA-selected studies, evaluating hydrogen enrichment in biodiesel-fueled engines. The analysis covers feedstock compatibility, performance impacts, and emission trade-offs, as well as key combustion characteristics.

It should be noted that the fuel property data presented in Table 4 were reported directly from the respective cited studies. Consequently, several measurement conditions, including testing temperatures for density and kinematic viscosity, differ across references due to the standards and experimental procedures adopted by each author. In addition, certain fuel properties were not reported in some original studies. Therefore, the table is intended to provide a general overview of biodiesel feedstock diversity rather than a strict one-to-one quantitative comparison between fuels.

The various types of biodiesel feedstocks used in dual-fuel configurations are summarized in Table 4. A review of the physical characteristics of non-conventional biodiesel fuels tested, such as Thevetia peruviana methyl ester (METP), waste cooking oil (WCO), and biofuel derived from Jamun fruit, reveals a consistent pattern in which the density and kinematic viscosity of biodiesel are higher than those of fossil diesel. This increase in viscosity and density inherently affects fuel atomization in the combustion chamber, potentially leading to larger fuel droplets and less efficient mixing [20, 35, 48]. Furthermore, biodiesel derived from feedstocks such as Moringa or Honne generally has a lower calorific value than conventional diesel, implying that a greater mass of fuel is required to produce the same energy output [38, 56].

In the context of fuel property modification for dual-fuel systems, hydrogen has unique thermal characteristics that offset the limitations of biodiesel. Hydrogen exhibits an exceptionally high gravimetric energy density (120 MJ/kg) and a significantly wider flammability range than liquid fuels [26, 38]. Its high laminar flame speed plays a vital role in enhancing the combustion characteristics of the mixture, offsetting the relatively slower combustion of biodiesel due to its elevated viscosity [52].

Chemically, the oxygenated molecular structure of biodiesel provides intrinsic advantages by facilitating more complete carbon oxidation, thereby reducing CO and hydrocarbon (HC) emissions [20, 56]. However, the presence of oxygen within the fuel chain, when interacting with the high adiabatic temperatures generated by hydrogen combustion, creates thermal conditions conducive to the formation of thermal NO_x. Despite this, hydrogen, as a carbon-free fuel, helps reduce PM and CO_2 emissions [35, 38].

3.2. Biodiesel fuel used in experimental research

The impact of hydrogen enrichment on engine performance is presented in Table 5. BTE is a crucial indicator of the efficiency of converting chemical energy into mechanical work. In general, the use of pure biodiesel (B100 or its blends) often reduces BTE due to its higher viscosity and LHV compared to diesel. However, hydrogen (H_2) enrichment consistently reverses this negative trend. Hydrogen possesses a flame speed significantly higher than that of diesel or biodiesel, which accelerates the combustion process and shifts the HRR closer to top dead center (TDC), thermodynamically approaching a more efficient constant-volume cycle. According to the study by Sathyanarayanan et al. [67], the addition of hydrogen to a microalgae biodiesel blend (A80P20) significantly improved BTE. The A80P20+H_2 mixture achieved up to 9.9% higher BTE than diesel at full load, primarily due to hydrogen's high diffusivity, which enhances air–fuel mixing. Similarly, Hoang et al. [29] reported that hydrogen enrichment of Mahua biodiesel (BDf20) at a flow rate of 10 l/min increased BTE by 16.75% compared to neat diesel.

Table 4. Fuel properties of various biodiesels based on raw materials

Types of biodiesels	Fuel properties							
	Density [kg/m³]	Calorific value/ LHV [MJ/kg]	Viscosity [mm²/s]	Cetane No.	Flash point [°C]	Fire point [°C]	Cloud point [°C]	Pour point [°C]
Sapota Seed Oil Methyl Ester (SOME) [54]	880	39.1	4.5	48	148	160	NR	NR
Jatropha Oil Methyl Ester (JOME) [69]	878	39.2	4.8	55	155	160	3	- 4
Soybean Biodiesel (B100) [70]	882.70 (20°C)	35.81	4.22 (40°C)	NR	169	NR	NR	NR
Soapnut Fruit Biodiesel (SFB) [14]	880	38.2	5.1	54	160	NR	4	NR
Garcinia Gummi-Gutta Methyl Ester (GGME) [55]	878	39.4	4.87	52	110	121	NR	NR
Spirogyra Biodiesel (SBD30) [4]	844.65 (15°C)	44.39	4.123 (40°C)	50.6	65	NR	NR	NR
Hydrotreated Vegetable Oil (HVO100) [61]	780 (15°C)	43.63	NR	74.3	NR	NR	NR	NR
Crude Palm Oil (CPO) [79]	875 (15°C)	39.91	4.5 (40°C)	56.7	140 (Min)	NR	NR	NR
Rice Bran Biodiesel Blend (RB-10) [43]	853	41.7	3.46	NR	90	NR	NR	NR
Honne Oil Biodiesel (BHO) [39]	880 (288 K)	39.8	4.5 (313 K)	44	187	NR	11	4
NR = not reported in the original study								

Table 5. Performance of a dual fuel diesel engine based on variations of factors used in the experiment

Author	Engine specifications	Method	Independent variables	Engine performance				EL
				BP	Torque	BSFC	BTE	
Elnajjar et al. (2022) [20]	Ricardo E6, 1-cylinder, 4-stroke, 0,5 liter, VCR (variable compression ratio)	Experiments	• Engine speed: 18, 21, 24, 27, 30 rev/sec • Hydrogen flow rate: 0–18.4 LPM • Pilot fuel flow rate (Biodiesel WCO): 9.92–15.79 mL/min • Ignition timing: 20–45° BTDC	Increase	Increase	–	Decrease	2–10 Nm
Munivenkaeshappa et al. (2024) [52]	Kirloskar TV1, 1-cylinder, 4-stroke, 0.638 L, CR 17.5:1	CFD experiments and simulations (ANSYS Fluent)	• Fuel: Diesel, Biodiesel B20 (Jackfruit & Black Cumin) + Graphene Amine Nanoparticles (60–100 ppm) • Injection Timing: 19°, 23°, 27°, 31° BTDC • Hydrogen flow rate (CFD): 0.10–0.20 kg/h	–	–	–	Increase	80% and 100% (5.2 kW)
Kannappan et al. (2023) [35]	Kirloskar AV-1, 1-cylinder, 4-stroke, 550 cc, 3.7 kW, CR 16.5:1	Experiments	• Fuel: Diesel, Biodiesel B20 (Syzygium cumini/Jamun) • Hydrogen Flow Rate: Fixed at 6 L/m3. EGR: 0%, 10%, 20%	–	–	Decrease (with hydrogen) and Increase (if added EGR)	Increase (with hydrogen) and decrease (if added EGR)	0%, 25%, 50%, 75%, 100%
Tutak et al. (2023) [75]	Andoria 1CA90, 1-cylinder, 4-stroke, 573 cc, 7 kW, CR 17:1	Experiments	• Liquid Fuel: Diesel vs. Biodiesel (RME) • Hydrogen Energy Share: 0%, 4%, 7%, 12%, 23%, 34%	–	–	Decrease	Increase by 7.85% with 24% hydrogen energy share	Constant maximum load
Christopher Selvam D et al. (2025) [14]	1-cylinder, 4-stroke, 5.2 kW, CR 17.5:1, Water-cooled	Experiments	• Fuel: Diesel, Biodiesel (Soapnut Fruit/SFB) • Hydrogen Fumigation: 10% of intake air • EL: varied	–	–	Decrease (7.1%)	Increase (6.0%)	0% 25%, 50%, 75%, 100%
Khandal et al. (2022) [38]	Kirloskar TV1, 1-cylinder, 4-stroke, 5.2 kW, CR 17.5:1	Experiments	• Fuel: Diesel vs. Biodiesel (Honey Oil/BHO) • Hydrogen Injection Method: Induction, Manifold Injection, Port Injection	–	–	–	Increase (highest in manifold injection method: 32% Diesel, 31.1% Biodiesel)	Constant 80%
Winangun et al. (2024) [79]	DI 800 H, 1-cylinder, 4-stroke, 411 cc, 4.47 kW, CR 18:1	Experiments	• Fuel: Biodiesel B100 (CPO) • Hydrogen Flow Rate: 2.5, 5, 7.5, 10 LPM • EL: Level Variations	Increase (increases as hydrogen is added)	–	Decrease (hingga 27.57%)	Increase in BTE with increasing hydrogen flow rate, reaching a maximum of 20.12% at 10 LPM	1000 W, 2000 W, 3000 W, 4000 W

At the saturation point of hydrogen enrichment (air displacement phenomenon), there is an optimal hydrogen flow rate. Beyond this limit, BTE decreases. Figure 3 shows that when the hydrogen flow increased from 10 L/min to 12 L/min (light blue bar), BTE dropped by about 3.26% compared to 10 L/min. Excess hydrogen displaces the intake air, reducing the oxygen available for complete biodiesel combustion. This also increases heat loss to cylinder walls due to higher combustion temperatures.

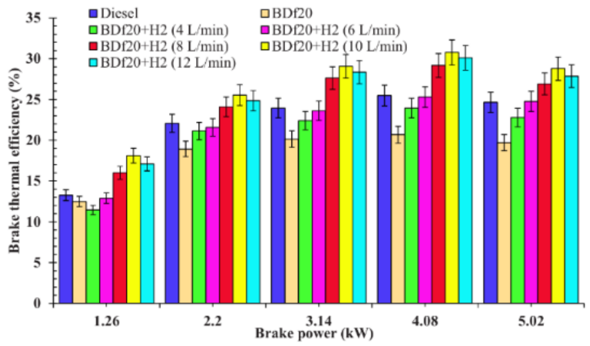

Fig. 3. BTE (%) with respect to engine brake power (kW) for diesel [29]

BSFC measures the efficiency of liquid fuel consumption per unit of power. In dual-fuel mode, BSFC reduction is highly significant because hydrogen supplies part of the energy, which has an exceptionally high gravimetric energy density (120 MJ/kg vs 42 MJ/kg for diesel). Consequently, hydrogen addition drastically reduces the required liquid fuel injection to achieve the same load. For example, data from Aravind et al. [4] showed a significant reduction in BSFC: at full load, the combination of SBD30 + 1.5%, DTBP + 2%, ARCNP + 15 L/min H_2 resulted in a BSFC of 0.12 kg/kWh, substantially lower than neat diesel (0.24 kg/kWh). This reduction is attributed to the rapid and complete combustion triggered by hydrogen and nanoparticles.

Dual-fuel diesel engines generally maintain or slightly increase brake power at full load compared with neat diesel due to more complete combustion. Hydrogen addition raises CP, torque, and crankshaft output, as shown by Aravind et al. with MCP reaching 81.6 bar at 20 L/min compared to 75.7 bar for diesel [4].

Table 6. Quantitative synthesis of engine performance

Performance parameter	Trend	n (studies included)	Mean effect size (%)	95% CI lower	95% CI upper
Brake thermal efficiency (BTE)	improved ↑	5 [20], [75], [14], [38], [79]	13.84	–0.70	28.38
Brake specific fuel consumption (BSFC)	reduced ↓	3 [75], [14], [79]	13.29	–17.30	43.88

Table 7. Emission of a dual-fuel diesel engine based on variations of factors used in the experiment

Author	Engine specifications	Method	Independent variables	Engine emission	EL
Simon et al. (2025) [70]	Generator set, 1-cylinder, 4-stroke, air-cooled. Power: 10 HP (nominal)	Experiment + Optimization (RSM) Design: Central Composite Design (CCD)	• Biodiesel Conc.: 15%, 22.5%, 30% (B15-B30). • Load • Hydrogen: Without H_2 vs With H_2 (13.3% in biogas).	• CO: ↓ ~5% (H_2 effect). • HC: ↓ 4.1% (H_2 effect). • NOx: ↑ 26.6% (H_2 effect), but dual-fuel overall is 11.5% lower than neat diesel.	1.5 kW – 4.5 kW
Periyathambi et al. (2025) [58]	Kirloskar TV1, 1-cylinder, 4-stroke, VCR, water-cooled.Power: 5.2 kW @ 1500 rpm	Experiment + Optimization (RSM)	• Injection Timing (IT): 24°, 27°, 30°, 33° bTDC. • H2 Flow Rate: 4, 8, 12, 16 LPM. • Fuel: Biodiesel C120 (Calophyllum Inophyllum).	• CO: ↓ 48%. • HC: ↓ 22.2%. • Smoke: ↓ 34.3%. • NO_x: ↑ 6.3%.(Optimal condition: IT30 + 16 LPM H_2).	25%, 50%, 75%, 100%
Sathyamurthy (2025) [66]	Kirloskar, 1-cylinder, 4-stroke, water-cooled.Power: 3.2 kW @ 1500 rpm	Experiment	• H2 Flow Rate: 0, 2, 4 LPM. • Fuel: Diesel vs Fish Oil Biodiesel (B20).	• CO: ↓ 45.7%. • HC: ↓ 22%. • CO_2: ↓ 6.9% (due to H_2 substitution). • NO_x: ↑ 17.1%.(Comparing B20+4LPM H_2 vs Diesel).	40, 60, 80 Nm (1750 rpm)
Nayak et al. (2025) [55]	Kirloskar TV1, 1-cylinder, 4-stroke, DI, water-cooled.Power: 5.02 kW @ 1500 rpm	Experiment	• Biodiesel Blend (GGME): 10%, 15%, 20%, 25%, 30%. • H_2 flow rate: Fixed at 5 L/min. • Fuel: Garcinia gummi-gutta Methyl Ester.	• CO: ↓ 21.05%. • HC: ↓ 13.04%. • Smoke: ↓ 25.61%. • CO_2: ↑ 25.64%. • NO_x: ↑ 5.12%.(Best blend GGME_15 + H_2).	0% 20% 40% 60% 80% 100%
Nalla et al. (2025) [54]	Kirloskar TV1, 1-cylinder, 4-stroke, DI, water-cooled. Power: 5.2 kW @ 1500 rpm	Experiment	• Biodiesel blend (SOME): B10, B20, B30 (Sapota Seed). • H_2 flow rate: 0.5, 1.0, 1.5 L/min (1.0 L/min selected as optimal).	• CO: ↓ 38%. • HC: ↓ 34%. • Smoke: ↓ 25%. • NO_x: ↑ 9.6%.(comparing B20+H_2 vs Diesel).	Full Load
Zhang et al. (2024) [85]	Marine Diesel Engine 4190Z (4-cylinder, turbocharged). Validated with 1-cyl experimental data	Simulation (CFD - CONVERGE) + Experiment (Validation) + Optimization (RSM)	• Hydrogen fraction: 0%, 5%, 10%, 15%. • EGR rate: 0%, 5%, 10%, 15%. • Fuel: Biodiesel-Hydrogen.	• NOx: ↓ significantly with EGR (e.g., down 65.3% at 15% EGR), but H_2 increases NO_x. • HC: ↓ with H_2 addition (down 39.7%), but increases with EGR. • Soot: ↑ with EGR.	Full Load (1750 rpm)
Khandal et al. (2024) [39]	Kirloskar TV1, 1-cylinder, 4-stroke, water-cooled.Power: 5.2 kW @ 1500 rpm	Experiment + Optimization (RSM & ANN) + ML (SVR, k-NN)	• Compression ratio (CR): 15.5, 16.5, 17.5.2. • H_2 flow rate (HFR): 0.1, 0.17, 0.24 kg/h. • Combustion chamber: HCC, TRCC, TCC. • Fuel: Honge (BHO) & Uppage (BUO).	• Smoke: ↓ 5-9% (with TRCC) • HC: ↓ 20-22%. • CO: ↓ 58-62%. • NO_x: ↑ 20-29% (Dual Fuel Mode vs Single CI Mode).	0% 25% 50% 75% 100%

As shown in Table 6, the addition of hydrogen generally improved the performance of biodiesel-fueled CI engines. On average, BTE increased by 13.84%, indicating a more efficient conversion of fuel energy into useful engine output. At the same time, BSFC decreased by 13.29%, suggesting that less fuel was required to produce the same amount of power. These improvements are largely associated with the favorable combustion characteristics of hydrogen, which promote faster and more complete combustion. Despite some variation among the reviewed studies due to differences in engine configurations and operating conditions, the overall findings consistently indicate that hydrogen enrichment can enhance the performance of biodiesel-powered CI engines.

3.3. Biodiesel fuel used in experimental research

The emission results for the dual-fuel diesel engine, along with various factors, are shown in Table 7. Collectively, these studies suggest that integrating hydrogen into bio-fueled diesel cycles induces a fundamental shift in combustion chemistry that extends beyond simple fuel substitution. This is primarily due to changes in chemical stoichiometry that favor complete oxidation. For instance, Oni et al. [56] demonstrated using a Petter PH1W engine that a blend of hybrid HCNG and 10% Moringa biodiesel (Sample D) reached an optimal oxidation point. This specific blend reduced CO_2 by 11.9% and drastically cut CO emissions by 27% at peak load compared to base HCNG.

This optimization trend is clearly visualized in Fig. 4, where the flattening of emission curves indicates improved combustion efficiency. Supporting this, Rodríguez-Fernández et al. [62] found a near-perfect linear correlation between the hydrogen-to-carbon ratio and CO_2 reduction using HVO and neat biodiesel. Under extreme conditions (90% hydrogen substitution), they observed a massive drop in CO_2 from 550 g/kWh to 50 g/kWh. As confirmed by the response surface patterns in Sagari et al. [42], the absence of carbon in hydrogen, combined with its high diffusivity and flame speed, facilitates the complete oxidation of liquid fuel droplets, thereby minimizing the formation of partial combustion products such as CO. Although hydrogen enrichment is generally associated with lower carbon emissions, CO_2 emissions do not consistently decline across all studies.

Nayak et al. [55] reported a 25.64% increase in CO_2 emissions when the GGME biodiesel blend ratio was increased under a constant hydrogen flow rate of 5 L/min. This phenomenon can be attributed to two main factors. First, increasing the biodiesel blend ratio introduces more carbon-containing fuel into the combustion chamber. Second, hydrogen promotes more complete oxidation of carbon species, facilitating the conversion of CO into CO_2. Therefore, under conditions in which combustion efficiency improves while the liquid fuel's carbon fraction remains high, CO_2 emissions may increase despite hydrogen enrichment.

Unburned hydrocarbons (UHC) or total hydrocarbons (THC) serve as critical indicators of combustion efficiency, where the interaction between biodiesel viscosity and hydrogen volatility plays a complex dual role. In general, hydrogen addition tends to reduce HC emissions because it widens the flammability limits of the fuel mixture, enabling flames to penetrate narrow crevices that are typically sources of HC emissions. This was demonstrated by Sagari et al. [42] using Niger seed biodiesel, where response surface plots showed a consistent decline in UHC with increasing hydrogen flow rate and EL. However, challenges arise when employing pilot fuels with extremely rapid combustion characteristics such as HVO. Rodríguez-Fernández et al. [62] observed anomalies at low loads, as shown in Fig. 5, where THC emissions increased at low-to-medium hydrogen ratios (below 50%). This phenomenon occurs because the very short ID of HVO causes pilot combustion to occur prematurely and separately from hydrogen combustion, resulting in insufficient local combustion chamber temperatures to fully oxidize lean fuel–air mixtures. Conversely, Marikatti et al. [48] emphasized that the injection strategy is critical in engines fueled with Thevetia peruviana biodiesel (METP). Optimized manifold hydrogen injection at 10° ATDC improved air–fuel mixing, effectively reducing HC emissions compared to conventional induction methods, despite the high viscosity of METP biodiesel that typically hampers atomization.

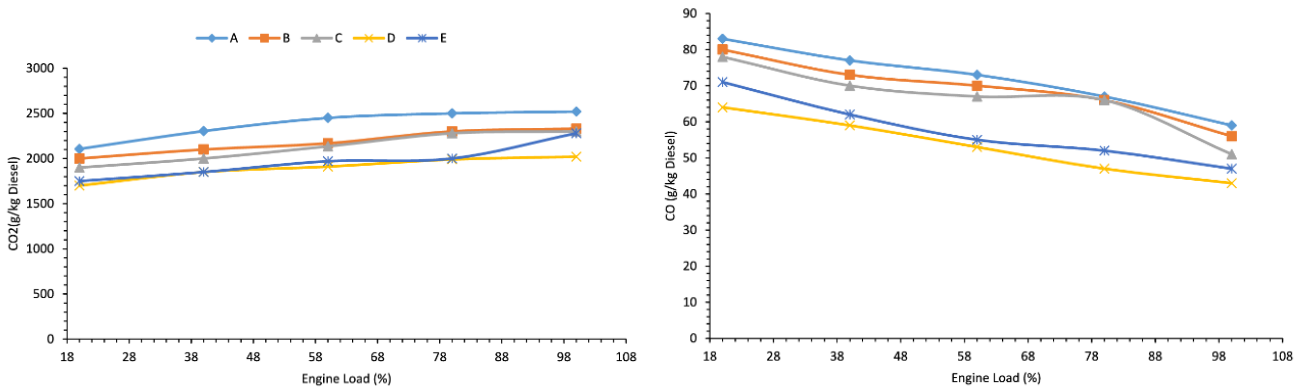

Fig. 4. CO and CO_2 concentration vs. EL for fuel blends A–E (A: 100% HCNG, B: HCNG + 5% Moringa biodiesel, C: HCNG + 7% Moringa biodiesel, D: HCNG + 10% Moringa biodiesel, and E: HCNG + 13% Moringa biodiesel) [56]

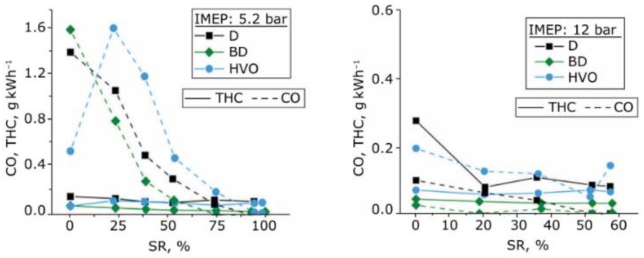

Fig. 5. PM emissions for different hydrogen energy ratios [76]

A significant advantage of integrating hydrogen into diesel engines is its capacity to disrupt the formation of soot and particulate matter (PM). As a carbon-free fuel, hydrogen eliminates soot precursors and raises local combustion temperatures, thereby promoting the oxidation of carbon particles. Rodríguez-Fernández et al. [62] observed that PM emissions dropped significantly at high loads, reaching near-zero levels when the hydrogen energy share surpassed 60%, as illustrated in Fig. 6. This reduction is notable as it further improves the emission profiles of HVO and biodiesel. While Sagari et al. [42] confirmed a linear reduction in smoke opacity with hydrogen addition, Marikatti et al. [48] identified a trade-off involving EGR. They noted that while hydrogen reduces smoke, the EGR required to mitigate NO_x restricts oxygen availability, potentially increasing smoke opacity again. Conversely, the primary challenge of hydrogen combustion remains the increase in NO_x emissions due to the thermal Zeldovich mechanism. The high adiabatic flame temperature of hydrogen causes rapid heat release and temperature spikes. Both Marikatti et al. [48] and Sagari et al. [42] found that NO_x levels are consistently higher with hydrogen, peaking at 1209 ppm under full load.

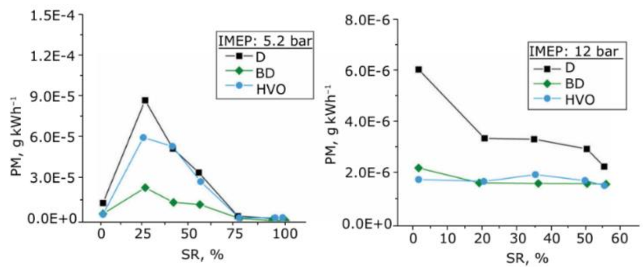

Fig. 6. PM emissions for different hydrogen energy ratios [76]

Although EGR has proven effective in mitigating NO_x emissions by lowering in-cylinder combustion temperatures, its application introduces important combustion trade-offs that must be considered carefully. Zhang et al. reported that increasing the EGR rate to 15% reduced NO_x emissions by up to 65.3% under biodiesel–hydrogen operation [85]. However, the same study also observed increases in HC and soot emissions due to reduced oxygen availability during combustion. This reduction in oxygen concentration can suppress oxidation reactions, potentially lowering combustion efficiency and deteriorating fuel conversion characteristics under excessive EGR conditions. Therefore, optimizing EGR application in biodiesel–hydrogen dual-fuel engines requires balancing NO_x mitigation against potential penalties to combustion stability, emissions formation, and engine performance.

Table 8. Quantitative synthesis of engine emission

Emission parameter	Trend	n (Studies included)	Mean effect size (%)	95% CI lower	95% CI upper
CO	reduction ↓	6 [70], [58], [66], [55], [54], [39]	36.29	15.29	57.29
HC	reduction ↓	7 [70], [58], [66], [55], [54], [85], [39]	22.29	11.23	33.35
NOx	increase ↑	6 [70], [58], [66], [55], [54], [39]	14.87	5.12	24.62
Smoke	reduction ↓	4 [58], [55], [54], [39]	22.98	4.73	41.22

As presented in Table 8, hydrogen enrichment generally improved the emission characteristics of biodiesel-fueled CI engines. CO, HC, and smoke emissions decreased by average values of 36.29%, 22.29%, and 22.98%, respectively, indicating more complete combustion and improved fuel oxidation within the cylinder. In contrast, NO_x emissions increased by an average of 14.87%, a trend commonly associated with higher combustion temperatures and enhanced combustion intensity resulting from hydrogen addition. Although the magnitude of emission changes varied across the reviewed studies, the overall trend suggests that hydrogen supplementation can significantly reduce incomplete-combustion pollutants while introducing a trade-off in the form of increased NO_x formation.

3.4. Biodiesel fuel used in experimental research

Table 9 is the result of the combustion characteristics of a dual-fuel diesel engine. An analysis of in-CP dynamics indicates that hydrogen addition generally increases peak pressure and shifts its timing toward Top Dead Center (TDC), though this behavior depends strongly on EL and gas flow rate. In the study by Tutak et al. [74], increasing the hydrogen energy fraction to 38% increased the maximum pressure by 1.2 MPa and advanced the timing of the peak pressure by 4 crank angle degrees, as shown in Fig. 7. These findings are supported by Yaliwal and Banapurmath, who observed that hydrogen enrichment in DiSOME–producer gas blends resulted in higher CP compared to operation without hydrogen, due to the increased laminar flame speed [80]. However, an interesting anomaly was reported at low loads by Winangun et al. [78], where a low hydrogen flow (2.5 L/min) triggered a sharp pressure spike caused by severe knocking due to early ignition, while a higher flow (10 L/min) reduced average pressure because of air displacement effects that lowered partial pressure.

The characteristics of the HRR undergo a fundamental transformation from a single-stage profile to a multi-stage profile dominated by kinetic phases as hydrogen concentration increases. Tutak et al. demonstrated a unique phenommenon in which, at a hydrogen fraction of 38%, a second HRR peak emerged, exceeding the first, indicating a drastic shift from diffusion combustion to an intense, rapid intermediate combustion phase [74]. This aligns with the findings of Mohanasundaram et al., who reported that hydrogen enrichment significantly enhanced the premixed combustion phase and shortened combustion duration by promoting the formation of OH and O radicals, which accelerate chemical reaction kinetics [50]. Yaliwal and Banapurmath further noted that the increase in HRR was also attributed to hydrogen's shorter quenching distance, which allows flames to propagate closer to cylinder walls without extinction, thereby improving overall heat-release efficiency [80].

Hydrogen's influence on combustion timing parameters shows varying results regarding ID. However, several studies have reported a shortening of total combustion duration. Tutak et al. found that ID remained nearly constant despite increasing hydrogen fractions. This was attributed to hydrogen's high auto-ignition temperature [74]. Yaliwal and Banapurmath reported a 6.8% reduction in ID in DiSOME-hydrogen operation. This was due to hydrogen's high diffusivity, which accelerates mixing [80]. Conversely, Winan-

Table 9. Combustion characteristics of dual fuel diesel engines fueled by biodiesel-hydrogen from selected studies

Author	Engine specifications	Method	Independent variables	Combustion characteristics			EL
				CP	HRR	ID	
Shabana et al. (2025) [69]	Kirloskar, 1-cylinder, 4-stroke, CI, 5.2 kW, 1500 rpm, CR 18:1.	Experiments	• Fuel Type: Diesel (D100), Jatropha Biodiesel (B20), B20+n-heptane (B20H10), B20H10+Nanoparticles (Al_2O_3, TiO_2, MWCNTs 60 ppm). • Hydrogen: 0 lpm, 6 lpm. • Load: 0–100%.	Increased by 33.3% in the B20H10+MWCNT+H2 blend compared to Diesel.	Increased by 9.14% in the B20H10+MWCNT+H_2 blend. ID: Decrease	ID reduced by adding H_2 and nanoparticles	0%, 25%, 50%, 75%, 100%
Jain et al. (2024) [33]	Kirloskar, 1-cylinder, 4-stroke, VCR, CR 17.5, 1500 rpm.	Experiment + Optimization (RSM)	• Injection pressure (FIP): 220, 240, 260 bar. • EL • Fuel: Blend of Water Hyacinth + Mesua Ferrea Biodiesel (WHMFB) + Hydrogen.	Increased with increasing FIP (Max 53.7 bar at 240 bar, up 24.27% compared to the base mode).	-	Decreases as FIP increases (15 to 13 degrees CA).	20%, 40%, 60%, 80%, 100%
Winangun et al. (2023) [78]	Diamond Type DI 800H, 1-cylinder, 4-stroke, 4.47 kW (continuous), 2000 rpm, CR 18:1.	Experiments	• Hydrogen flow: 0, 2.5, 5, 7.5, 10 lpm. • Fuel: Palm Oil Biodiesel (B100).	Increased by 8.98% (average) to 10% at 10 lpm H_2 flow compared to pure biodiesel.	Increased by approximately 5.33% compared to biodiesel.	Increases (longer) compared to pure biodiesel, but shorter than diesel at high loads.	80% Constant
Bora et al. (2024) [9]	1-cylinder, 4-stroke, 3.5 kW, 1500 rpm, Dual Fuel (Biogas + Emulsified Biodiesel).	Experiments + Optimization (RSM)	• Compression ratio (CR): 17, 17.5, 18. • Injection Timing (IT): 23, 26, 29, 32 CA bTDC. • Load: 20–100%.	Increased by 11.73% when CR increased to 18; increased by 20.06% when IT was advanced to 32° bTDC.	Peak HRR is delayed in Dual Fuel mode compared to diesel.	Decreases 5.47% as CR Increases 22.34% when IT is advanced.	20%, 40%, 60%, 80%, 100%
Hernández et al. (2023) [28]	Constant Volume Combustion Chamber (CVCC) - Not an engine, combustion characteristics tester (Volume 0.473 L).	Experiments (CVCC)	• Low Reactivity Fuel (LRF): H_2, NH_3, CH_4. • Energy Substitution: 10%, 20%, 40%. • Initial Temperature: 535°C, 600°C. • High Reactivity Fuel: Diesel, HVO, Biodiesel, OME20D.	Peak pressure decreased with increasing gas substitution due to incomplete combustion in the lean region.	Significant increase with the addition of LRF (NH_3 inhibits autoignition the most).	Pressure gradient (dp/dt) decreases with the addition of LRF.	N/A (Condition adjusted to match EL via fuel injection)
Laguado-Ramírez et al. (2024) [43]	SOKAN-MDF300, 1-cylinder, 300 cc, 3600 rpm.	Experiments + Economic/ Energy Analysis	• Fuel: Diesel (D-100%), Rice Bran Biodiesel (RB-10%), RB-10% + H2 (30% energy fraction).	Increased by 4.05% in the RB-10%+H_2 blend compared to RB-10%.	Increased by 6.40% in the RB-10%+H_2 blend compared to RB-10%.	-	20%, 40%, 60%, 80%, 100%
Rimkus & Žaglinskis (2024) [61]	Audi-VW 1.9 TDI (1Z), 4-cylinder, turbocharged, 66 kW, CR 19.5.	Experiments + Simulation (AVL BOOST)	• Gas Energy Share (GES): 40%, 60%, 80% (Biogas simulation). • H_2 addition: 10%, 20%, 30% of the gas volume. • Pilot Fuel: HVO100 vs D100.	Decreased with increasing biogas percentage, but the addition of H_2 increased the pressure again.	Increased in the premixed phase with the addition of H_2.	Addition of H2 shortens the delay caused by CO_2 in biogas.	BMEP = 0.6 MPa (medium load) at 2000 rpm
Sateesh et al. (2024) [65]	Kirloskar TV1, 1-cylinder, 4-stroke, 3.7 kW (table specifications) / 5.2 kW (text), 1500 rpm, CR 17.5.	Experiments	• Nanoparticles: AlO(OH), MWCNT, Al_2O_3 (Dosage: 20, 40, 60 ppm). • Fuel: Dairy Scum Oil Methyl Ester (DiSOME) + Producer Gas (PG).	Decreased by 8.6% in the DiSOME-PG mode compared to Diesel, but increased again with the addition of nanoparticles (AlO(OH)) best).	Decreased by 4.6% with DiSOME-PG, increased with nanoparticles.	Increases 10.8% in DiSOME-PG, decreases with the addition of nanoparticles.	80% (for combustion analysis)
Halewadimath et al. (2023) [26]	Kirloskar TV1, 1-cylinder, 4-stroke, 5.2 kW, 1500 rpm, CR 17.5.	Experiments + Optimization (RSM)	• Flow Rate: 0.4–0.8 kg/h. • Producer Gas Flow Rate: 7–9 kg/h. • H_2 Flow Rate: 0.029–0.059 kg/h.	Increases as the flow rate of H_2 and Biodiesel increases; Decreases as PG flow rate increases.	Increased with H_2 addition.	Decreases with the addition of H_2, increases with the addition of PG.	60% to 80%

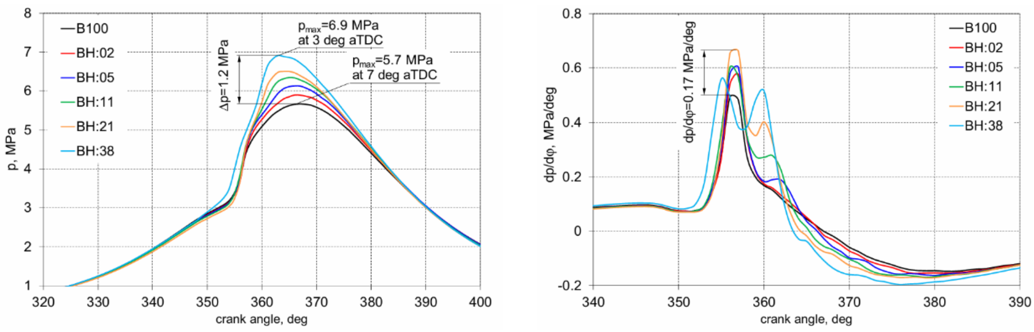

Fig. 7. Combustion pressure curve and pressure rise rate for different energetic shares of hydrogen [74]

gun et al. highlighted a critical correlation between ID and operational stability. The shortest ID occurred at 2.5 L/min flow and matched the highest knocking intensity. At a flow rate of 10 L/min, knocking was suppressed and stability improved [78].

Overall, the reviewed studies indicate that the influence of hydrogen on ignition delay is highly dependent on operating conditions, hydrogen substitution ratio, and biodiesel feedstock properties. Some studies reported a shorter ignition delay due to improved fuel-air mixing and accelerated reaction kinetics, whereas others observed a nearly constant or even prolonged ignition delay due to hydrogen's high autoignition temperature and air displacement effects at high flow rates. These variations demonstrate that ignition delay behavior in biodiesel-hydrogen dual-fuel engines cannot be generalized using a single trend.

As shown in Table 10, hydrogen enrichment generally enhanced the combustion characteristics of biodiesel-fueled CI engines. Cylinder pressure (CP) increased by an average of 13.85%, indicating stronger combustion and improved energy release within the cylinder. Likewise, the heat release rate (HRR) increased by 4.07%, reflecting a more rapid combustion process. In addition, ignition delay (ID) decreased by an average of 5.67%, indicating earlier combustion initiation due to hydrogen's higher reactivity and faster flame propagation. Despite variations among the included studies, the overall trends indicate that hydrogen addition promotes more efficient and stable combustion in biodiesel-operated CI engines.

Table 10. Quantitative synthesis of engine combustion characteristics

Combustion characteristics parameter	Trend	n (studies included)	Mean effect size (%)	95% CI lower	95% CI upper
Cylinder pressure (CP)	Enhancement ↑	6 [69], [33], [78], [9], [43], [65]	13.85	–1.95	29.66
Heat release rate (HRR)	Enhanced ↑	4 [69], [78], [43], [65]	4.07	–5.49	13.63
Ignition delay (ID)	Shortened ↓	2 [9], [65]	–5.67	–46.75	35.41

4. Discussion

4.1. Biodiesel fuel used in experimental research

This discussion synthesizes findings from selected studies to uncover the impact of hydrogen integration in biodiesel engines. To provide a holistic understanding of these complex interactions, Fig. 8 presents a conceptual framework mapping the identified physicochemical synergistic mechanisms and operational trade-off dilemmas. This framework serves as the foundation for the in-depth analysis outlined in the following subsections, from fuel properties to emission mitigation strategies.

4.2. Biodiesel fuel used in experimental research

This literature review reveals that hydrogen's role in dual-fuel diesel engines extends beyond serving as an additional energy source; it also corrects the crucial physicochemical properties of biodiesel. The fundamental issue with using biodiesel in CI engines is its higher kinematic viscosity and greater density compared to fossil diesel. These physical characteristics inherently hinder atomization, leading to the formation of large fuel droplets and poor mixing [20, 35, 48].

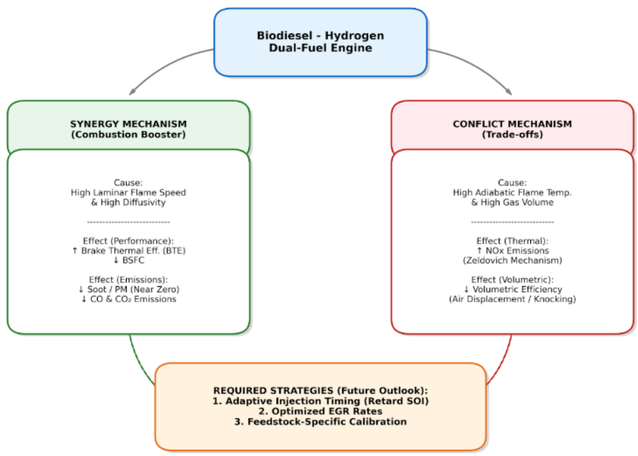

Fig. 8. Mechanisms of synergy, conflict, and adaptive strategies in dual-fuel engines

Hydrogen integration provides synergistic compensation through its superior thermal properties. Its high laminar flame speed and diffusivity accelerate flame propagation in the combustion chamber [52]. This has been shown in various studies by consistent increases in BTE. Hydrogen helps "burn out" slow-reacting biodiesel zones and greatly reduces BSFC [4, 29, 53, 67].

This mechanism transforms the combustion regime from one dominated by slow diffusion into rapid kinetic combustion, marked by increased peak CP and sharper HRR profiles [74, 80]. Thus, hydrogen effectively compensates for biodiesel's deficiencies in atomization, making this combination a technically viable solution for maintaining diesel engine performance.

4.3. The emissions trade-off dilemma: eliminating soot at the cost of NO_x

Cross-study analysis reveals a significant paradigm shift in emissions. The synergy of biodiesel–hydrogen offers a definitive solution to the classic problem of diesel engines: PM/soot emissions. Data indicate a drastic reduction in smoke opacity and PM, approaching near-zero emissions at high hydrogen energy ratios, due to hydrogen's carbon-free combustion characteristics [42, 56, 62]. This reduction is not merely proportional but structural; hydrogen disrupts the chain of soot precursor formation, while elevated local temperatures facilitate the oxidation of carbon particles [62].

However, these environmental benefits come at a thermodynamic penalty in the form of increased NO_x emissions. Indeed, nearly all reviewed literature reports NO_x increases that correlate linearly with hydrogen flow rates and EL [42, 48, 64]. This phenomenon underscores the dominance of the Thermal Zeldovich mechanism, whereby hydrogen's high adiabatic temperature triggers nitrogen oxidation [2, 71]. As a result, this trade-off dilemma, in which PM decreases sharply while NO_x rises, demands active mitigation strategies, such as retarding the SOI and employing EGR [48, 58].

4.4. Operational limits and feedstock sensitivity

Hydrogen enrichment can improve performance. However, this review finds a major operational limitation: the Air Displacement phenomenon. There is an optimal saturation point, usually at a flow rate of 10–12 LPM. Adding more hydrogen past this point is counterproductive [29]. Too much hydrogen pushes out incoming air, lowering volumetric efficiency. This explains why BTE falls at extremely high hydrogen flow rates [67, 77].

Volumetric limitations are not the only concern. Feedstock diversity adds complexity. Studies report different ID some report a shorter ID, while others report a constant or longer ID. This shows that the chemical interaction between hydrogen and biodiesel is very sensitive to properties of the original feedstock [74, 77, 80]. One injection strategy will not work for every dual-fuel engine. Instead, adaptive strategies that consider specific feedstock characteristics are needed to maintain combustion stability [11, 27].

4.5. Strategic directions for future research

The literature consistently shows that adding hydrogen improves biodiesel's combustion, compensating for its high viscosity and lower energy content. This leads to higher BTE and reduced BSFC [4, 29, 53, 67], while always cutting carbon emissions (CO, CO_2) and soot (PM) because hydrogen burns quickly and is carbon-free [42, 56, 62].

However, results differ across studies for ID, which depends on fuel type and injection method [74, 77, 81]. There is also a common trade-off in emissions: reducing soot often increases NO_x emissions because higher combustion temperatures are associated with higher NO_x emissions [42, 48, 64].

Therefore, future research directions should focus on developing precision injection strategies such as calibrated SOI adjustments and EGR to mitigate NO_x without sacrificing thermal efficiency [48, 58]. Additionally, a deeper investigation into the critical threshold of hydrogen flow rate (saturation point) is required to avoid the air-displacement phenomenon, which has been shown to reduce volumetric performance under excessive flow conditions [67, 77].

4.6. Limitations of the review

This review has several limitations that should be acknowledged. The literature search was restricted to open-access journal articles indexed in the Scopus database to ensure full-text accessibility and consistency during data extraction and analysis. However, this selection approach may introduce publication bias, as several relevant studies published in subscription-based journals may not have been included in the review. Therefore, the findings presented in this study should be interpreted as representing the currently accessible open-access literature within the selected database and review period.

In addition, a formal statistical meta-analysis was considered unsuitable for the present review due to the substantial heterogeneity among the selected studies. The reviewed articles employed highly diverse experimental conditions, including differences in engine configuration, operating load, biodiesel feedstock properties, hydrogen substitution ratio, injection strategy, and combustion enhancement methods. In several cases, the same performance or emission parameter exhibited both increasing and decreasing trends depending on the operating conditions. Consequently, direct statistical pooling and effect-size averaging could potentially lead to misleading conclusions. For this reason, the present study adopts a qualitative comparative synthesis approach to identify recurring trends and operational patterns across biodiesel–hydrogen dual-fuel CI engine studies.

5. Conclusion

This systematic review provides a comprehensive analysis of research on dual-fuel biodiesel–hydrogen engines, highlighting feedstock diversity, injection strategies, and combustion and emission characteristics. Recommendations and future research directions are also highlighted for researchers and stakeholders interested in the decarbonization of CI engines. The conclusions are as follows:

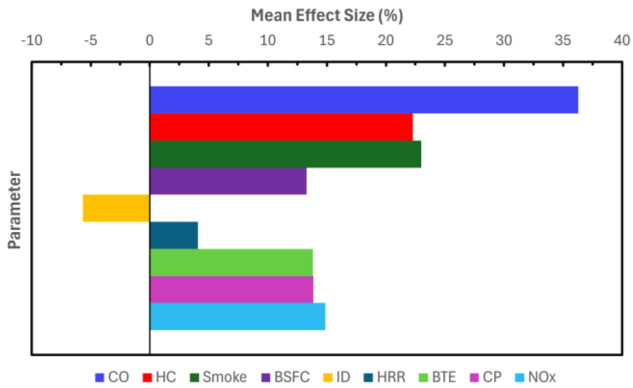

Fig. 9. Diverging bar chart showing the average effects of hydrogen enrichment on engine performance, combustion characteristics, and emissions

- The use of hydrogen as a combustion booster helps offset biodiesel's high viscosity (resistance to flow) and low calorific value. Strategies such as retarding the SOI, employing EGR, and optimizing hydrogen flow rates have been applied to reduce NO_x emissions from the Zeldovich mechanism (NO_x formation process at high temperatures) and prevent air displacement (the reduction in oxygen when another gas is introduced).
- Combustion characteristics, performance, and emissions are significantly improved by hydrogen enrichment, as summarized in Fig. 9, as evidenced by increased BTE, reduced BSFC, and drastic reductions in CO, CO_2, and PM emissions. Achieving these improvements while controlling CP spikes and NO_x emissions requires careful optimization of hydrogen-to-oxygen ratios.
- Addressing the sensitivity of ID to different biodiesel feedstocks and developing adaptive injection strategies to manage the NO_x–soot trade-off are critical research directions in dual-fuel biodiesel–hydrogen engine technology.

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Nomenclature

BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CI	compression ignition
CO	carbon monoxide
CO_2	carbon dioxide
EGR	exhaust gas recirculation
EL	engine loads
HRR	heat release rates
NO_x	nitrogen oxide
PM	particulate matter
SLR	systematic literature review
SOI	start of injection
TDC	top dead center

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