Synergistic Effects of Citrullus Colocynthis Biodiesel and Hydrogen on Combustion and Emission Characteristics of CI Engines

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Abstract

The growing demand for low-carbon and sustainable fuels has intensified research on alternative fuel combinations for compression ignition (CI) engines. In this study, the synergistic effects of biodiesel and hydrogen enrichment on the combustion and emission characteristics of a CI engine were experimentally investigated. The engine was operated at a constant speed of 1500 rpm under varying load conditions using diesel (D), biodiesel blend (B20), and hydrogen-enriched biodiesel with hydrogen energy shares of 5%, 10%, and 15%. Cylinder pressure and heat release rate (HRR) were analyzed using a piezoelectric pressure transducer coupled with crank angle measurement. Results indicated that hydrogen enrichment increased the peak cylinder pressure by 6–12% compared to neat biodiesel operation, with a corresponding rise in the maximum heat release rate of 15–28% due to enhanced premixed combustion. The ignition delay was reduced by 8–18%, while combustion duration shortened by 10–20%, reflecting improved combustion efficiency. Emission analysis showed a substantial reduction in carbon monoxide (CO) emissions by 25–45%, unburned hydrocarbons (HC) by 20–40%, and smoke opacity by 30–55% under hydrogen-enriched conditions. However, nitrogen oxides (NO_x) emissions increased by 6–15%, attributed to elevated in-cylinder temperatures and accelerated combustion kinetics. Brake thermal efficiency improved by 3–8%, while brake-specific fuel consumption decreased by 4–10% relative to biodiesel operation. Overall, the results demonstrate that biodiesel–hydrogen dual-fuel operation significantly enhances combustion performance and reduces carbon-based emissions, highlighting its potential as an effective transitional solution for cleaner CI engine technology.

1. Introduction

Compression ignition (CI) engines are essential for stationary power generation, transportation, and agricultural machinery because of their exceptional fuel efficiency, durability, and operational dependability. However, the widespread usage of diesel fuel produced from petroleum has sparked grave worries about the depletion of fossil fuels, greenhouse gas emissions, and degradation of urban air quality. Research attempts to find low-emission, sustainable alternative fuels for CI engines have increased due to strict emission laws and international pledges to carbon neutrality [1]. A viable alternative to traditional diesel fuel is biodiesel, which is made from renewable feedstocks such vegetable oils, animal fats, and leftover cooking oils. Because of its natural oxygen concentration, greater cetane number, and biodegradability, it burns more efficiently and emits less particulate matter, carbon monoxide (CO), and unburned hydrocarbons (HC). However, burning biodiesel frequently has certain disadvantages, such as increased viscosity, a reduced calorific value, and a propensity to increase emissions of nitrogen oxides (NO_x). These restrictions prevent biodiesel from being widely used, especially in heavy-duty and high-load engine applications [2]. Because of its zero-carbon combustion, broad flammability limitations, low ignition energy, and remarkably high flame propagation speed, hydrogen is becoming more widely acknowledged as a clean and sustainable energy source. Hydrogen can dramatically increase combustion intensity, speed up heat release, and lower carbon-based pollutants when used as an additional fuel in CI engines. However, issues including pre-ignition, backfire, knock, and increased NO_x production due to high in-cylinder temperatures limit the direct usage of hydrogen in CI engines. As a result, hydrogen works best when utilized in dual-fuel mode, which uses a liquid fuel as a pilot for ignition control [3]. The use of hydrogen and biodiesel together offers a synergistic strategy that maximizes the benefits of both fuels while reducing their respective drawbacks. While hydrogen improves premixed combustion and encourages more thorough oxidation of fuel-rich regions, biodiesel is a dependable pilot fuel that guarantees stable ignition and smooth engine performance. Biodiesel's oxygenated composition enhances diffusion-controlled burning and prevents soot formation, which further enhances hydrogen combustion. In addition to increasing engine efficiency, this synergistic interaction may also lower hazardous emissions [4]. While a number of research have examined hydrogen and biodiesel separately in CI engines, there are still few thorough experimental studies that concentrate on their combined effects, especially with regard to in-depth combustion study. Cylinder pressure development, heat release rate (HRR), ignition delay, and combustion length are examples of in-cylinder combustion variables that have received less attention than performance and emission outcomes in many previous research. Furthermore, more thorough analysis is needed to determine how the hydrogen energy share affects combustion phasing and emission trade-offs under different load situations [5]. In this regard, the current study is to experimentally examine the complementary impacts of hydrogen enrichment and biodiesel on the combustion and emission characteristics of a CI engine. The main liquid fuel used is biodiesel, and variable energy shares of hydrogen are introduced into the intake manifold. Using in-cylinder pressure data, a thorough combustion study is carried out to assess peak pressure, HRR, rate of pressure rise, ignition delay, and combustion duration. In order to evaluate the environmental advantages and trade-offs related to biodiesel–hydrogen dual-fuel running, regulated exhaust emissions are also examined. It is anticipated that the results of this study will provide important information for the development of cleaner and more effective CI engine technologies that use renewable fuel mixtures [6]. Because of its oxygen content and generally higher cetane number, biodiesel (fatty acid methyl/ethyl esters from vegetable oil, animal fat, or waste oils) has been shown to improve combustion completeness compared to mineral diesel; these characteristics typically lower CO, HC, and particulate matter emissions. However, a number of studies show that biodiesel mixes tend to produce more NO_x under similar operating conditions. This is explained by changes in in-cylinder temperature and spray/atomization characteristics, earlier combustion phasing, and increased local oxygen availability. Technical papers and review articles provide a summary of these mechanisms and mitigation strategies [7]. It has been repeatedly reported that hydrogen addition (intake enrichment or direct gas injection) improves premixed combustion, increases flame speed, and shifts peak heat-release toward TDC, resulting in higher peak in-cylinder pressures and faster heat-release rates, improved thermal efficiency, and significant reductions in smoke, CO, and HC. Although the NO_x response relies on hydrogen share, load, speed, and whether EGR or injection timing modifications are performed, the literature consistently finds increases in NO_x at moderate to high hydrogen energy shares due to higher peak temperatures and more intense combustion. Hydrogen energy share ranges are covered by a number of reviews and experimental research (average experimental values: 0–15% for small-share studies; other studies go much higher, up to ~ 30–50% energy share). The trade-offs between research are summarized in the [8] review: Hydrogen can enhance BTE and BMEP, however unless countermeasures are taken, NO_x typically increases.

Increases in peak cylinder pressure (few percent to ~ 10% for modest hydrogen sharing) and HRR that correspond with better premixed combustion [10] have been reported in experimental investigations [9]. An increasing number of experimental studies specifically examine the dual-fuel functioning of biodiesel and hydrogen. Reduced smoke/CO/HC, slight gains in thermal efficiency, increased peak pressure and HRR, and a minor rise in NO_x (which some authors manage with EGR or re-timed injection) are typical reported effects [9]. The engine and fueling system determine the maximum possible hydrogen energetic share; some studies estimate energetic replacement of up to ~ 30–40% while maintaining stable operation. [10] describe co-combustion testing that demonstrated a significant decrease in smoke and a rise in peak in-cylinder pressure/HRR, with hydrogen replacement up to ~ 34–38% energy share being possible in single-cylinder configurations. Consistent tendencies are confirmed by recent experimental work: lower CO/HC/smoke, higher BTE, and lower BSFC, with NO_x increases that scale with hydrogen share unless controlled [11]. NO_x management is crucial since both hydrogen and biodiesel have a tendency to increase peak combustion temperatures (for somewhat different causes). Exhaust gas recirculation (EGR), injection timing retardation, and combination control (EGR + timing + hydrogen share tuning) are all tried-and-true laboratory techniques. Numerous publications have measured NO_x reductions using mild EGR (10–25%) or delaying injection timing; however, under certain situations, these methods may increase soot or offset some of the efficiency advantages (trade-offs are engine and operating-point dependant). [12] demonstrate that delaying injection and using EGR can effectively reduce NO_x from biodiesel. The same strategies can be applied to biodiesel–hydrogen systems, however optimization is needed to prevent BSFC degradation or particulate matter growth. Beyond cylinder-level outcomes, new research addresses the significance of hydrogen in decarbonizing heavy-duty fleets and the necessity of assessing infrastructure, techno-economic viability, well-to-wheel CO_2, and the green versus grey hydrogen production pathway. Research shows that although adding hydrogen can significantly lower tank-to-wheel CO_2 (proportional to hydrogen energy share), LCA and cost analysis are necessary for a comprehensive sustainability assessment [13]. Due to its advantageous oxygen concentration and renewable nature, Citrullus colocynthis biodiesel has been shown in numerous experimental experiments to be a suitable non-edible alternative fuel for compression ignition (CI) engines. However, the majority of current studies pay little attention to sophisticated combustion enhancement methods and instead concentrate on single-fuel biodiesel operation or biodiesel–diesel mixes. The synergistic relationship between hydrogen enrichment and Citrullus colocynthis biodiesel has not been thoroughly investigated, despite the fact that hydrogen enrichment has been frequently documented to increase combustion efficiency and lower carbon-based emissions in CI engines. Comprehensive research on the combined effects of hydrogen induction and Citrullus colocynthis biodiesel on in-cylinder combustion parameters, emission trade-offs (NO_x–smoke), and overall engine performance under different load circumstances is particularly lacking. Furthermore, when using non-edible biodiesel fuels, ideal hydrogen flow rates and their effects on combustion stability and emission production mechanisms are not well understood in the literature currently under publication. To fill this research gap, a thorough experimental study is required to determine the advantages and disadvantages of hydrogen-assisted Citrullus colocynthis biodiesel combustion in CI engines. The objective of this study is to experimentally investigate the synergistic effects of *Citrullus colocynthis* biodiesel and hydrogen enrichment on the combustion and emission characteristics of a compression ignition (CI) engine. The work aims to evaluate engine performance, combustion behavior, and exhaust emissions under different operating conditions and hydrogen flow rates, and to compare the results with conventional diesel operation. The study also seeks to identify an optimum hydrogen-assisted biodiesel operating condition that enhances combustion efficiency while reducing harmful emissions, thereby assessing the feasibility of *Citrullus colocynthis* biodiesel–hydrogen dual-fuel operation as a sustainable alternative for CI engines.

2. Materials and Methods

2.1 Citrullus colocynthis Biodiesel Preparation

Citrullus colocynA traditional transesterification method was used to create this biodiesel. After gathering mature fruits, the seeds were cleaned, sorted, and dried in the sun and oven to remove any remaining moisture before being ground into a fine powder. Using a Soxhlet system and n-hexane as the solvent, oil was extracted from the powdered seeds. Crude oil was then obtained by solvent recovery. Titration was used to measure the extracted oil's free fatty acid (FFA) content; if the FFA value was higher than 2%, acid esterification was performed using methanol and sulfuric acid to lower the FFA level. The pre-treated oil was then reacted with methanol in the presence of potassium hydroxide at a regulated temperature and stirring conditions to carry out base-catalyzed transesterification.

Following the reaction, the liquid was allowed to settle, which caused the layers of biodiesel and glycerol to separate. The biodiesel layer was dried to eliminate moisture after being cleaned with warm distilled water to get rid of any remaining catalyst, soaps, and contaminants. Citrullus colocynthis methyl ester biodiesel was the end result, which is appropriate for additional physicochemical analysis and engine performance assessment (Fig. 1).

3. Experimental setup

An eddy current dynamometer was used in conjunction with a single-cylinder, four-stroke, water-cooled compression ignition (CI) engine for precise load management and performance evaluation. To test various operating circumstances, the load was changed while the engine ran at a steady 1500 rpm. The traditional fuel injection system was used to supply diesel and biodiesel blends, and a calibrated burette and stopwatch approach was used to measure fuel usage. A regulated supply system comprising a pressure regulator, non-return valve, flame arrestor, and mass flow controller was used to induct hydrogen gas (quality > 99.9%) into the intake manifold. This allowed for hydrogen energy shares of 5%, 10%, and 15%, with biodiesel serving as the pilot fuel. A piezoelectric pressure transducer synced with a crank angle encoder (1° CA resolution) was used to monitor in-cylinder pressure, which was then recorded using a high-speed data collecting system. Pressure data from 100 consecutive cycles were averaged for combustion analysis. After the engine attained steady-state operation, an optical smoke meter was used to evaluate smoke opacity and a calibrated exhaust gas analyzer was used to quantify exhaust emissions of CO, HC, and NO_x (Fig. 2).

3.1 Uncertainty Analysis

To evaluate the accuracy of the observed and computed parameters, an uncertainty analysis was carried out. Instrument specifications were used to evaluate the uncertainties related to important data, including fuel flow rate, air flow rate, cylinder pressure, crank angle, and emission concentrations. The root-sum-square approach was used to determine the total uncertainty in derived parameters, such as brake thermal efficiency (BTE), heat release rate, and combustion time. For experimental engine studies, the highest uncertainty was found to be within ± 2–4% for performance metrics and ± 3–5% for emission data.

4. Results and discussion

4.1 Brake Thermal Efficiency (BTE)

Figure 3 shows how engine load affects brake thermal efficiency for diesel, B20, B20 + H_2 (2 L/min), and B20 + H_2 (4 L/min). Because of improved combustion characteristics, hydrogen enrichment greatly increases BTE over the load range, with B20 + H_2 showing the maximum efficiency at 4 L/min. Under all load conditions, brake thermal efficiency gradually rises from diesel to hydrogen-enriched B20 operation. Due to comparatively slower combustion and restricted oxidation of fuel-rich regions, diesel operation produces the lowest BTE. Because biodiesel's natural oxygen content promotes more thorough combustion and better use of the fuel energy delivered, the B20 biodiesel mix exhibits a moderate improvement in BTE. BTE further improves when hydrogen is added to B20 at a rate of 2 L/min. This is because hydrogen improves the premixed combustion phase, shortens the duration of combustion, and increases flame propagation. The highest BTE is obtained by increasing the hydrogen flow rate to 4 L/min. This is because the faster heat release near top dead center enhances effective pressure development and lowers heat losses. In comparison to both pure diesel and B20 operation, the results show that biodiesel and hydrogen have a substantial synergistic impact that improves thermal efficiency.

4.2 Specific Fuel Consumption

Figure 4 shows how specific fuel consumption for diesel, B20, and hydrogen-enriched B20 fuels varies with engine load. Due to increased combustion efficiency and partial substitution of liquid fuel energy, hydrogen addition dramatically lowers SFCE throughout the load range, with B20 + H_2 showing the lowest value at 4 L/min. For all test fuels, specific fuel consumption drops as engine load increases because of increased combustion efficiency and decreased relative heat losses. Throughout the load range, diesel operation has the highest SFCE, which indicates less efficient fuel use. Because biodiesel is oxygenated, which increases fuel oxidation and combustion, the B20 blend exhibits a slight decrease in SFCE when compared to diesel. SFCE is found to significantly decrease with hydrogen enrichment. SFCE significantly drops at all loads with B20 + H_2 at 2 L/min because of increased premixed combustion and faster flame propagation, which increases energy conversion efficiency. With B20 + H_2 at 4 L/min, where hydrogen contributes a fraction of the total energy intake and encourages more complete combustion, SFCE is further reduced. Consequently, for this fuel mixture, the lowest SFCE values are observed at greater loads. Overall, the findings show that hydrogen enrichment enhances the fuel efficiency of B20-fueled CI engines in a synergistic way.

4.3 NOx Emission

Figure 5 shows how engine load affects nitrogen oxide (NOx) emissions for diesel, B20, and hydrogen-enriched B20 fuels. For all fuels, NOx emissions rise with load; in hydrogen-enriched situations, greater values are seen because of higher in-cylinder temperatures and faster combustion. Because of the increase in in-cylinder temperature and pressure at higher loads, nitrogen oxide (NOx) emissions grow with engine load for all test fuels. At low and medium loads, diesel running exhibits somewhat lower NOx emissions. The oxygenated nature of biodiesel and higher combustion temperatures are the primary causes of the B20 blend's small increase in NOx when compared to diesel. NOx emissions rise even more with hydrogen enrichment, especially for B20 + H_2 at 2 L/min and 4 L/min. greater peak combustion temperatures, which promote thermal NOx generation, are a result of hydrogen's greater flame speed and quick heat release. Because of increased premixed combustion and extra oxygen availability, B20 + H_2 exhibits the highest NOx levels at 4 L/min, particularly at full load. Overall, hydrogen enrichment increases NOx emissions despite increasing efficiency and lowering carbon-based emissions; this suggests the necessity for mitigating techniques such EGR, water injection, or injection timing retardation.

4.4 Hydrocarbon (HC) Emissions

Figure 6 shows how engine load affects unburned hydrocarbon (HC) emissions for diesel, B20, and hydrogen-enriched B20 fuels. Because of better flame propagation and more thorough combustion, HC emissions fall with increasing load and hydrogen induction, reaching their lowest values for B20 + H_2 at 4 L/min. For all test fuels, hydrocarbon emissions decrease as engine load increases because of improved combustion temperature and increased oxidation of unburned fuel at higher loads. Due to incomplete combustion in locally rich and quenching zones, diesel operation exhibits the highest HC emissions. Because biodiesel contains oxygen, which promotes more thorough combustion, the B20 biodiesel blend produces lower HC emissions than diesel. Hydrogen enrichment considerably lowers HC emissions at both 2 L/min and 4 L/min flow rates. Hydrogen facilitates better combustion in lean and low-temperature areas of the cylinder by increasing flame speed and stability. B20 + H_2 produces the lowest HC emissions at 4 L/min, demonstrating the potent synergistic effect of hydrogen and biodiesel in lowering unburned hydrocarbon emissions in CI engines.

4.5 Carbon Monoxide (CO) Emissions

Figure 7 shows how carbon monoxide (CO) emissions for diesel, B20, and hydrogen-enriched B20 fuels change with engine load. Because of higher combustion efficiency and the carbon-free nature of hydrogen, CO emissions fall with increasing load and hydrogen enrichment, with the lowest values recorded for B20 + H_2 at 4 L/min. For all test fuels, carbon monoxide emissions decrease as engine load increases because higher in-cylinder temperatures facilitate better carbon monoxide to carbon dioxide oxidation. Due to incomplete combustion, diesel operation results in relatively higher CO emissions, particularly under low and part-load situations. Because the oxygenated character of biodiesel improves combustion efficiency and oxidation of carbon-rich zones, the B20 biodiesel blend exhibits lower CO emissions than diesel. CO emissions are greatly reduced with hydrogen enrichment at both 2 and 4 L/min flow rates. Hydrogen reduces CO production and promotes more thorough burning since it is a carbon-free fuel that enhances flame propagation. Biodiesel and hydrogen work together to improve combustion quality and lower carbon monoxide emissions in CI engines, as evidenced by the lowest CO emissions recorded for B20 + H_2 at 4 L/min.

4.6 Smoke Emissions

Figure 8 shows how the smoke opacity of diesel, B20, and hydrogen-enriched B20 fuels changes with engine load. For all fuels, smoke emissions rise with load; however, hydrogen enrichment dramatically lowers smoke opacity, with B20 + H_2 showing the lowest values at 4 L/min because hydrogen is carbon-free and improves the oxidation of soot precursors. Due to increased fuel injection amounts and locally rich combustion zones at high loads, smoke emissions rise with engine load for all test fuels. Due to incomplete combustion and increased soot precursor generation, diesel operation results in the maximum smoke opacity. Because biodiesel's natural oxygen content promotes the oxidation of soot particles during combustion, the B20 biodiesel blend exhibits fewer smoke emissions than diesel. For both 2 L/min and 4 L/min flow rates, smoke emissions are greatly decreased by hydrogen enrichment. Because hydrogen doesn't contain carbon, it reduces the production of soot and increases the homogeneity of combustion, which increases the oxidation of soot. Biodiesel and hydrogen have a considerable synergistic effect in reducing particle and smoke emissions in CI engines, as evidenced by the lowest smoke opacity for B20 + H_2 at 4 L/min.

4.7 Cylinder Pressure

Figure 9 shows how the in-cylinder pressure for diesel, B20, and hydrogen-enriched B20 fuels varies with crank angle. Because of faster premixed combustion and increased heat release close to top dead center, hydrogen enrichment accelerates combustion phasing and raises peak cylinder pressure. The greatest peak was recorded for B20 + H_2 at 4 L/min. When compared to diesel, biodiesel–hydrogen operation clearly improves combustion characteristics as evidenced by cylinder pressure variation with crank angle. Diesel fuel has a longer diffusion-controlled phase and slower combustion, which results in a comparatively lower peak cylinder pressure. Because of better combustion made possible by the oxygen in the biodiesel, the B20 blend exhibits a slight increase in peak cylinder pressure. Peak cylinder pressure increases significantly with hydrogen enrichment, particularly for B20 + H_2 at 2 L/min and 4

L/min. By decreasing ignition delay and boosting flame speed, hydrogen improves premixed combustion and causes a quick release of heat close to top dead center. B20 + H_2 has the highest peak cylinder pressure at 4 L/min, suggesting better pressure development and increased combustion intensity. Overall, the considerable synergistic effect of hydrogen and biodiesel on combustion performance in CI engines is confirmed by the increase in cylinder pressure.

4.8 Heat Release Rate

Figure 10 shows how the heat release rate (HRR) for diesel, B20, and hydrogen-enriched B20 fuels varies with crank angle. With the greatest HRR recorded for B20 + H_2 at 4 L/min, hydrogen enrichment raises the peak premixed heat release rate and moves combustion closer to top dead center. Enhanced premixed combustion with hydrogen enrichment is seen from the heat release rate profiles. Diesel's HRR peak is wider and lower, indicating slower combustion that is dominated by the diffusion phase. Because of better combustion made possible by the oxygen in the biodiesel, the B20 mix exhibits a little rise in peak HRR. A stronger and sharper premixed HRR peak is seen with hydrogen addition at 2 L/min, suggesting a shorter ignition delay and quicker flame propagation. The maximum HRR peak appears closer to top dead center when the hydrogen flow rate is increased to 4 L/min, indicating quick energy release and enhanced combustion intensity. Although higher peak heat release may contribute to increased NOx production, the HRR data generally indicate the considerable synergistic effect of hydrogen and biodiesel in improving combustion efficiency.

Conclusion

The present study investigated the synergistic effects of biodiesel (B20) and hydrogen enrichment on the performance, combustion, and emission characteristics of a compression ignition engine. The experimental results demonstrate that hydrogen induction significantly enhances engine performance when operated with B20 biodiesel. Brake thermal efficiency increased and specific fuel consumption decreased with hydrogen addition, with the best performance observed at a hydrogen flow rate of 4 L/min. These improvements are attributed to the high flame speed, wide flammability range, and superior diffusivity of hydrogen, which promote faster and more complete combustion. Combustion analysis revealed higher peak cylinder pressure and increased premixed heat release rate for hydrogen-enriched B20 operation, indicating improved combustion intensity and better combustion phasing near top dead center. Emission analysis showed substantial reductions in carbon monoxide, unburned hydrocarbons, and smoke opacity with hydrogen enrichment due to the carbon-free nature of hydrogen and enhanced oxidation processes. However, nitrogen oxide emissions increased with higher hydrogen flow rates as a result of elevated in-cylinder temperatures and accelerated combustion. Overall, the combined use of biodiesel and hydrogen presents a promising dual-fuel strategy for improving efficiency and reducing carbon-based emissions in CI engines. The increase in NOx emissions suggests the need for suitable mitigation techniques such as exhaust gas recirculation, water injection, or injection timing optimization. Future work may focus on optimizing hydrogen induction rates and integrating NOx control strategies to achieve an optimal balance between performance enhancement and emission reduction.

Declarations

Funding

The authors confirm that no funding or financial assistance was received for the conduct, authorship, or publication of this research article.

Clinical Trial Number

Not applicable.

Ethics, Consent to Participate, and Consent to Publish

Not applicable.

Data Availability Statement

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request

Plant Source Information

Details regarding the source of Citrullus colocynthis seeds have been added to the Methods section. The seeds used in this study were collected from naturally growing plants in the semi-arid region near Ramanathapuram district, Tamil Nadu, India (approximate coordinates: 9.37° N, 78.83° E).

Compliance with Plant Collection Guidelines

A statement confirming compliance with local and national guidelines for plant collection has been included in the Ethics Declaration section. The study complied with institutional and regional regulations governing the collection and utilization of plant materials.

Plant Identification

The manuscript now includes the name of the botanist who authenticated the plant material. The collected plant specimens were taxonomically identified and authenticated by Dr. P. Balu, Department of Automobile, BIHER, India.

Herbarium Deposition

Information regarding voucher specimen deposition has been added. Voucher specimens were deposited in the Herbarium of the Department of Automobile, BIHER, India.

Voucher Specimen ID

The voucher specimen number has been explicitly included in the manuscript and Ethics Declaration section as follows:

Voucher specimen No.: CC-2026-017

Permissions and Licences

The collection of plant materials complied with applicable institutional, regional, and national guidelines. Necessary permissions for collection of plant specimens from non-protected areas were obtained prior to sample collection.”

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Figures

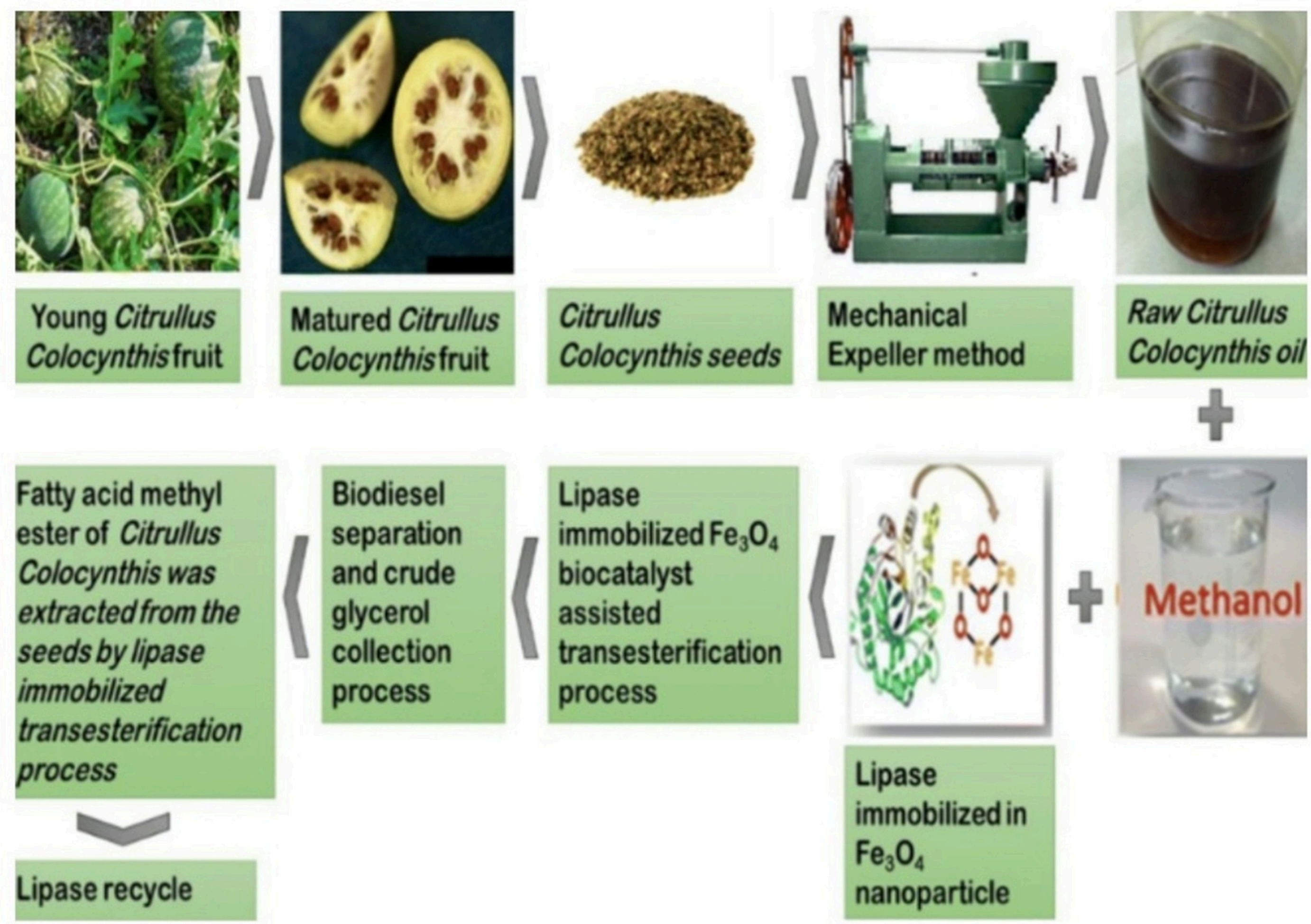

Figure 1

Citrullus colocynthis Biodiesel Preparation

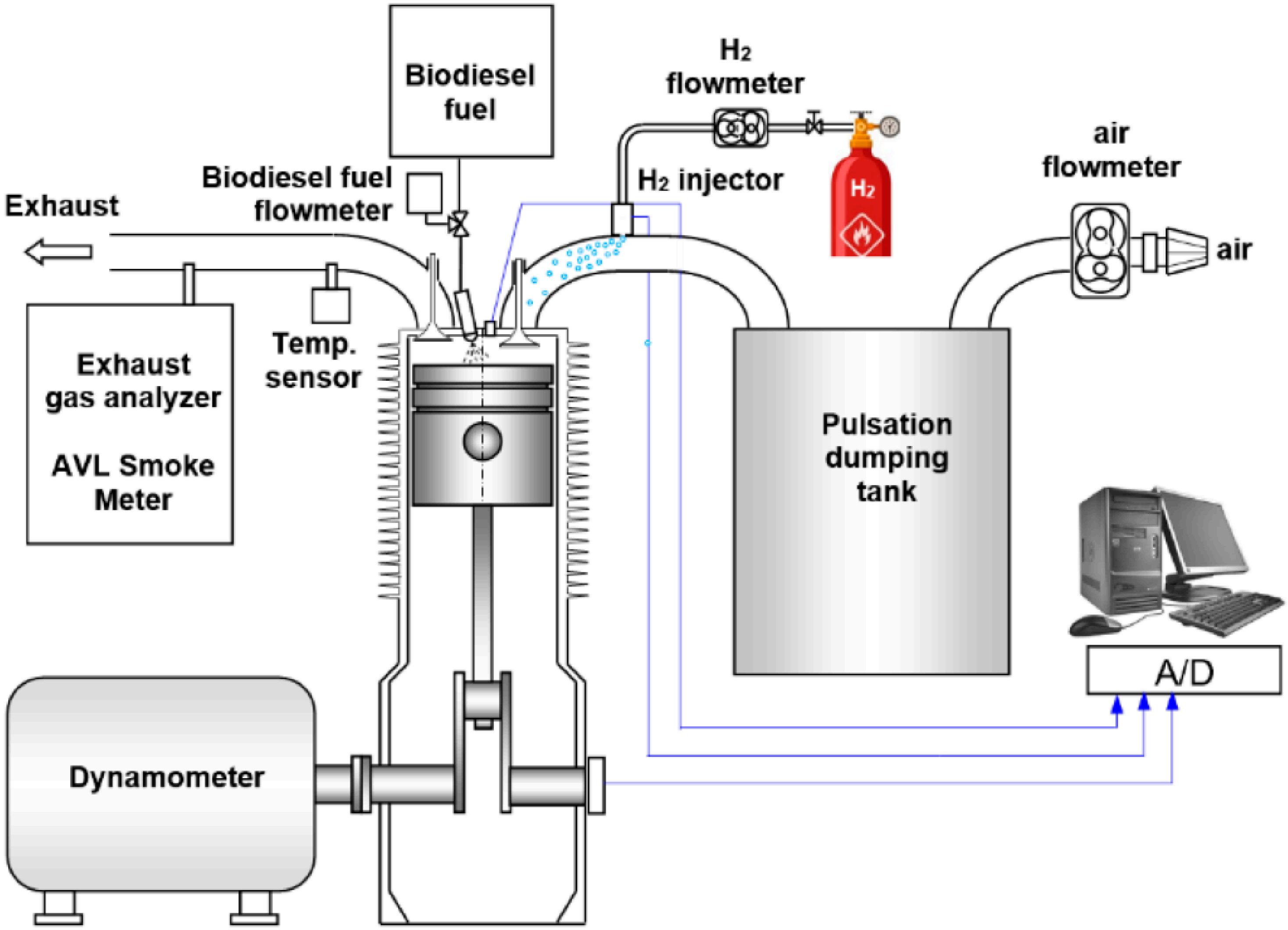

Figure 2

Experimental setup

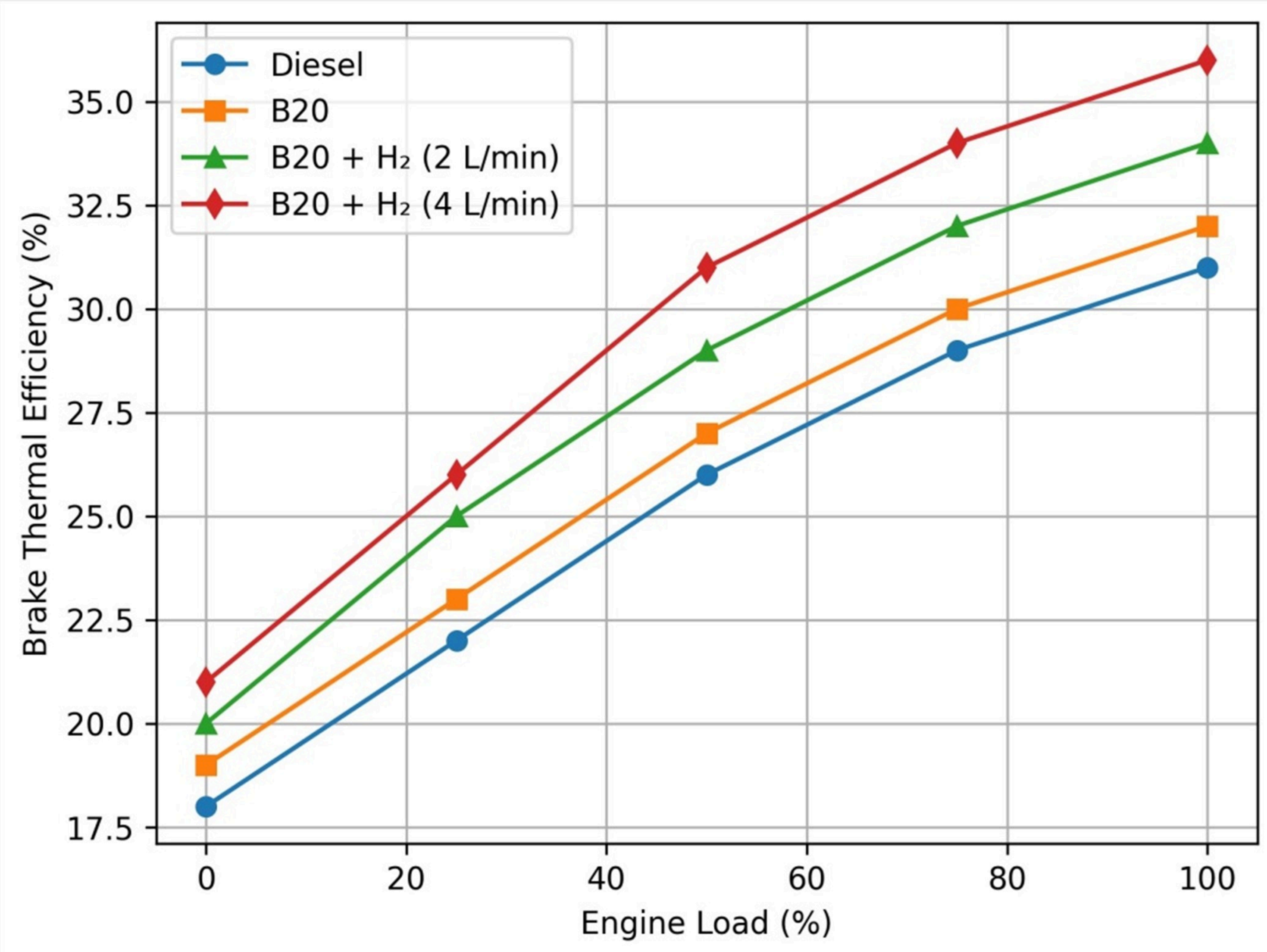

Figure 3

Variation of brake thermal efficiency with engine load

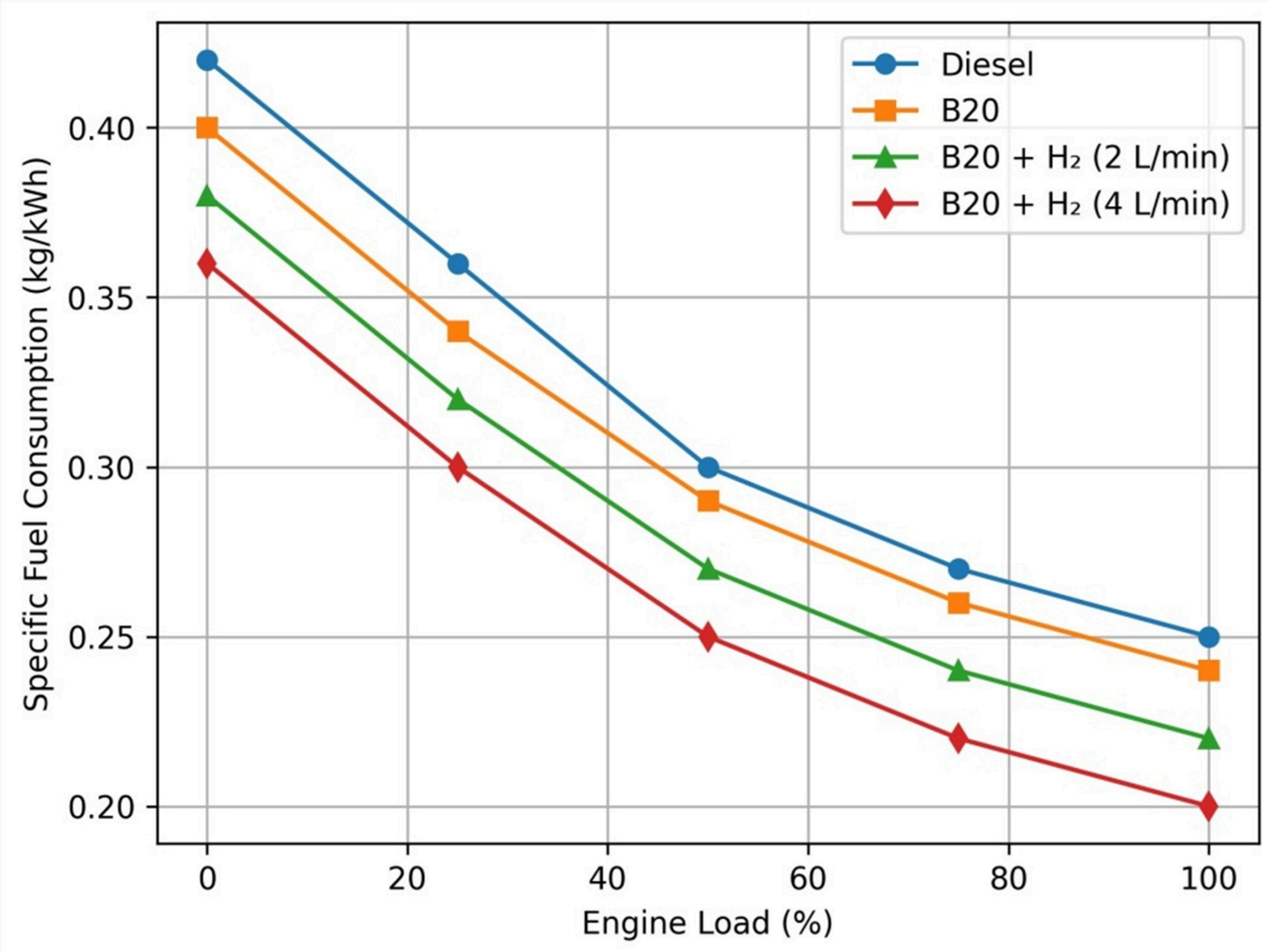

Figure 4

Variation of specific fuel consumption with engine load

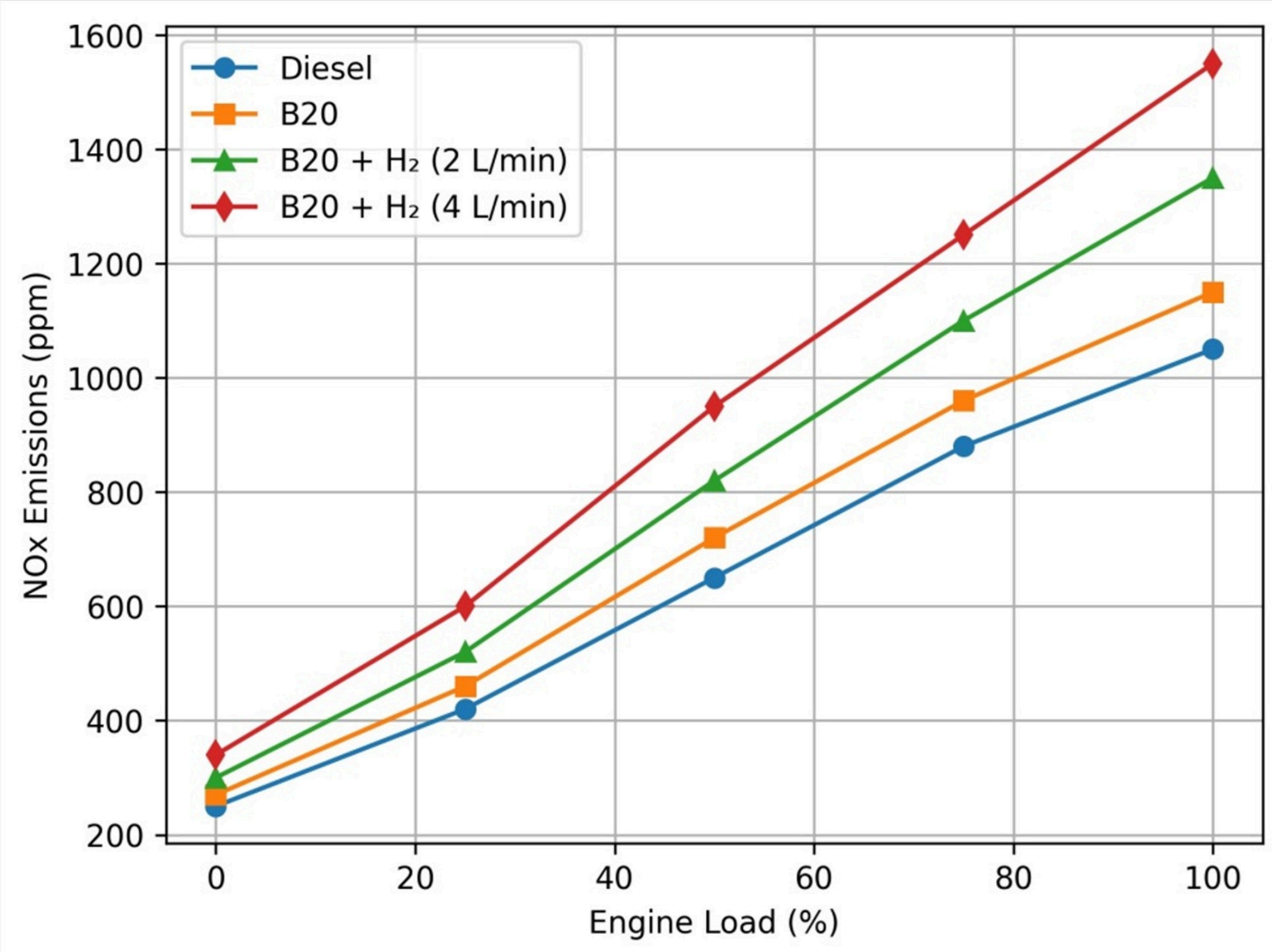

Figure 5

Variation of nitrogen oxide (NOx) emissions with engine load

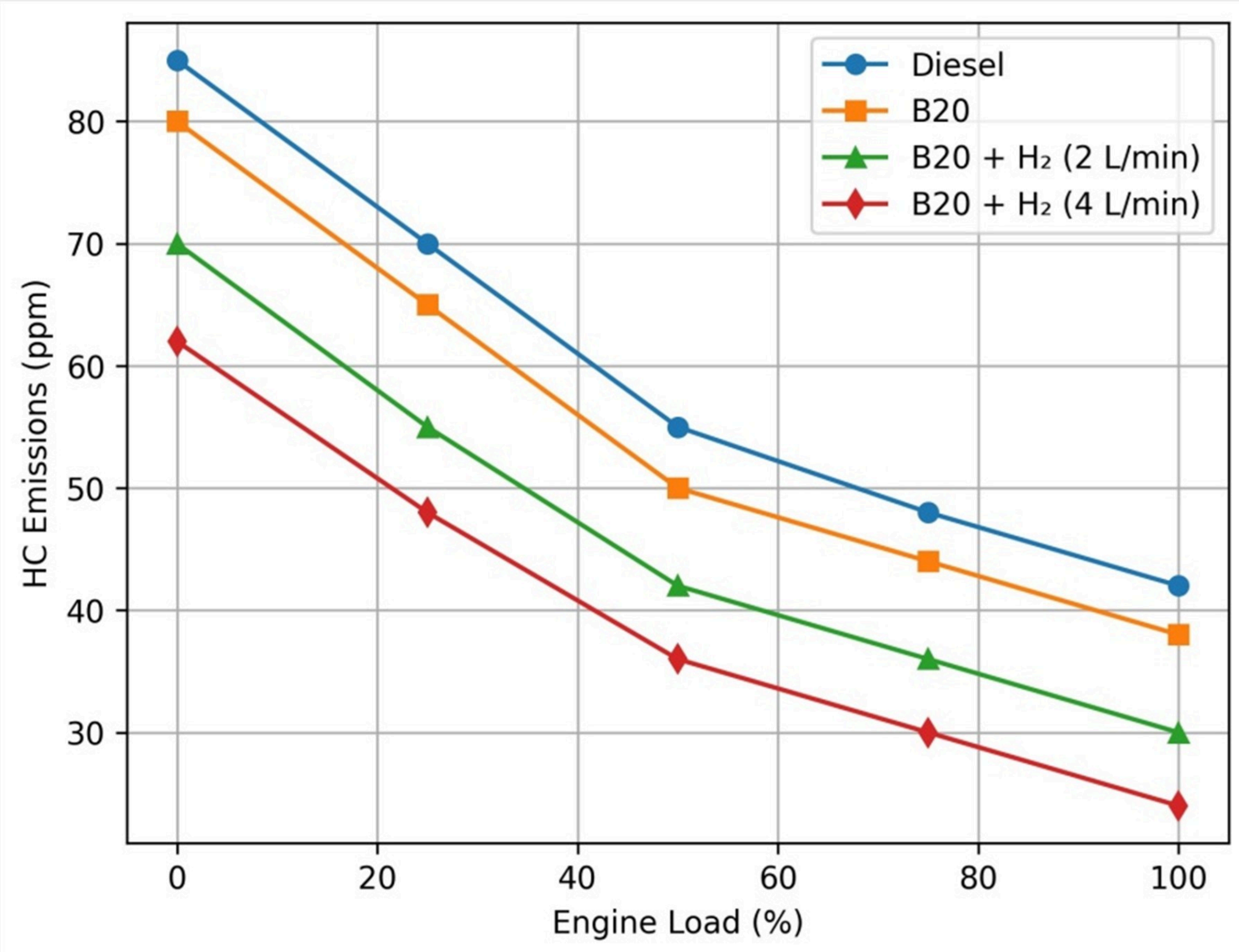

Figure 6

Variation of unburned hydrocarbon (HC) emissions with engine load

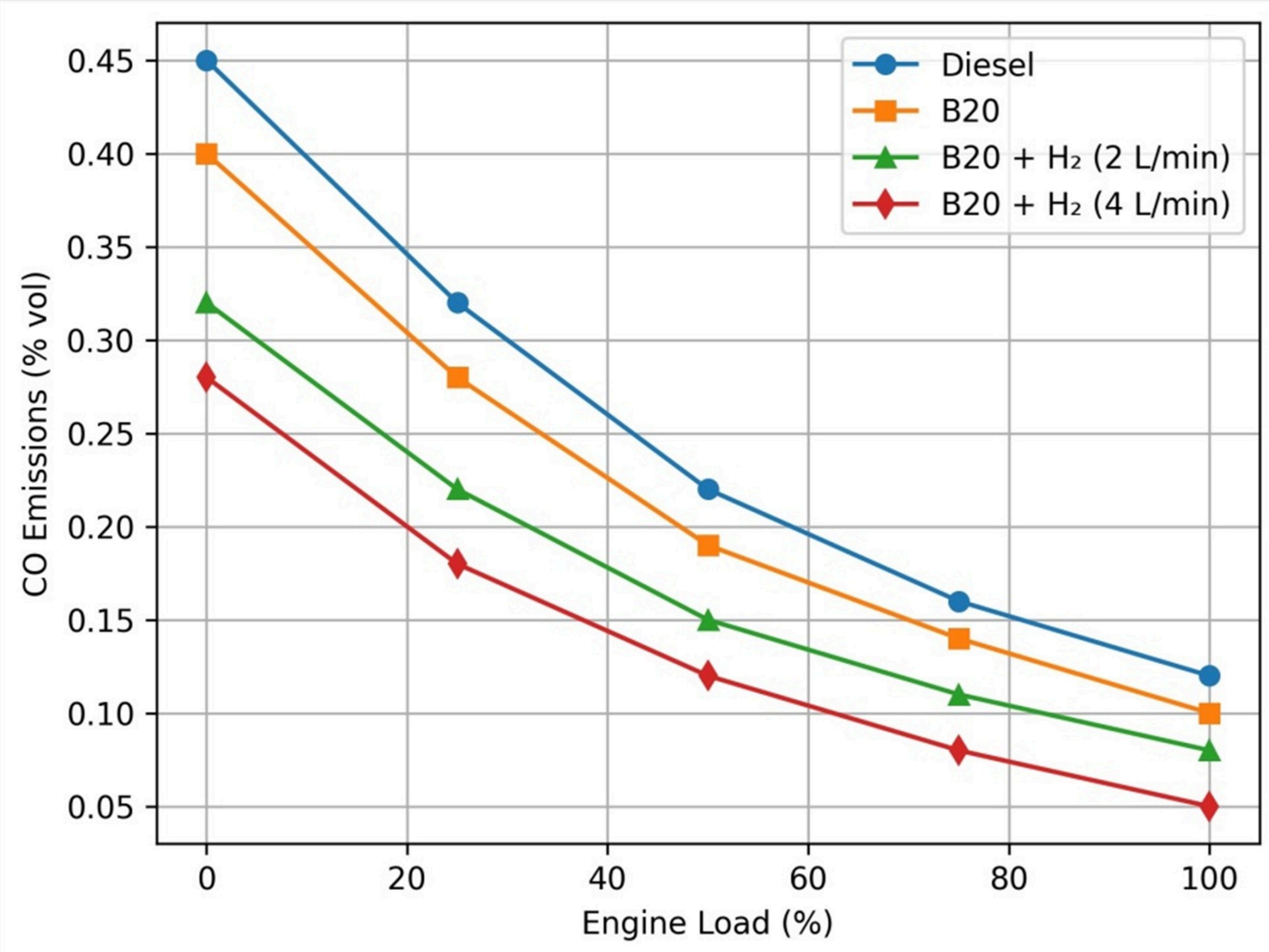

Figure 7

Variation of carbon monoxide (CO) emissions with engine load

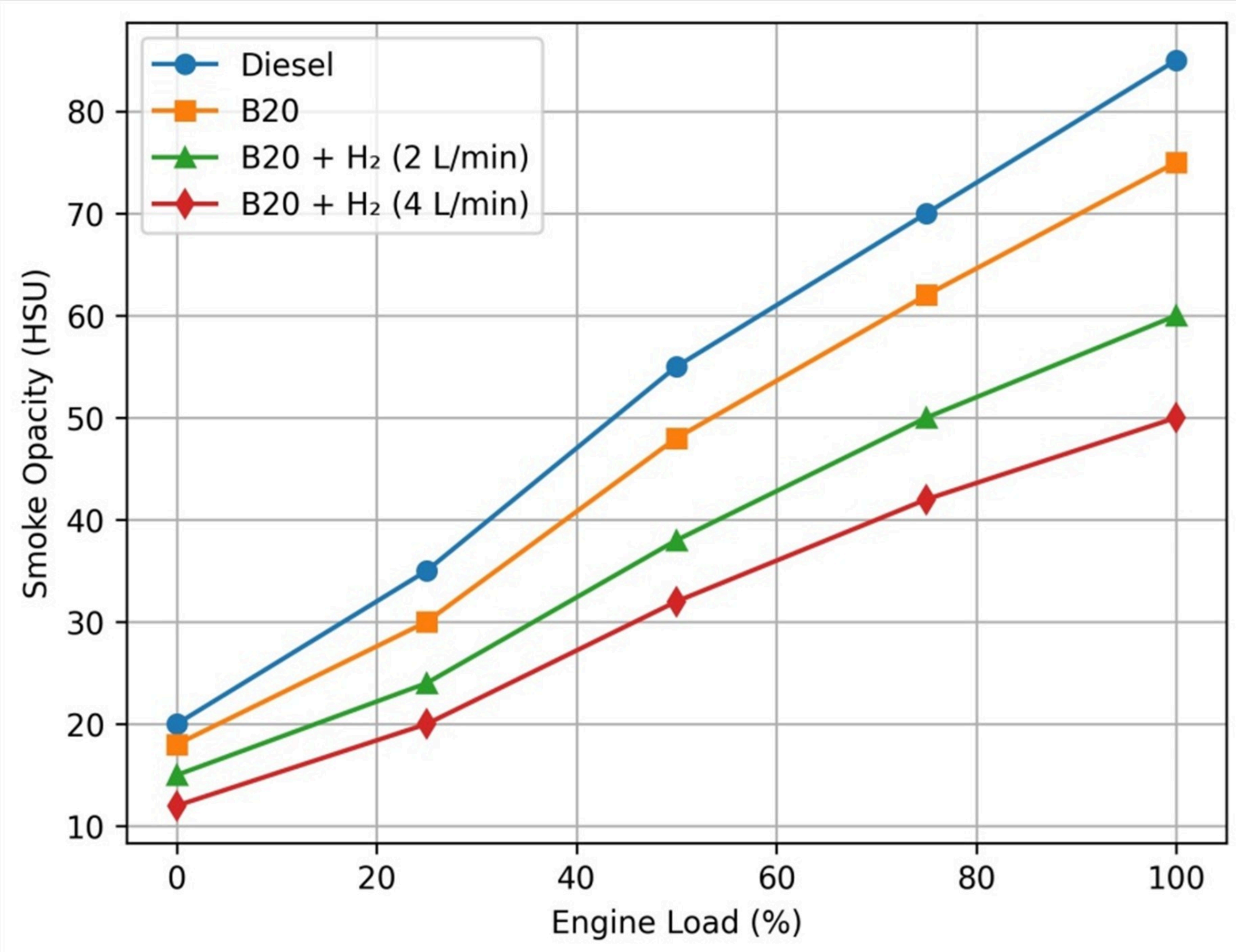

Figure 8

Variation of smoke opacity with engine load

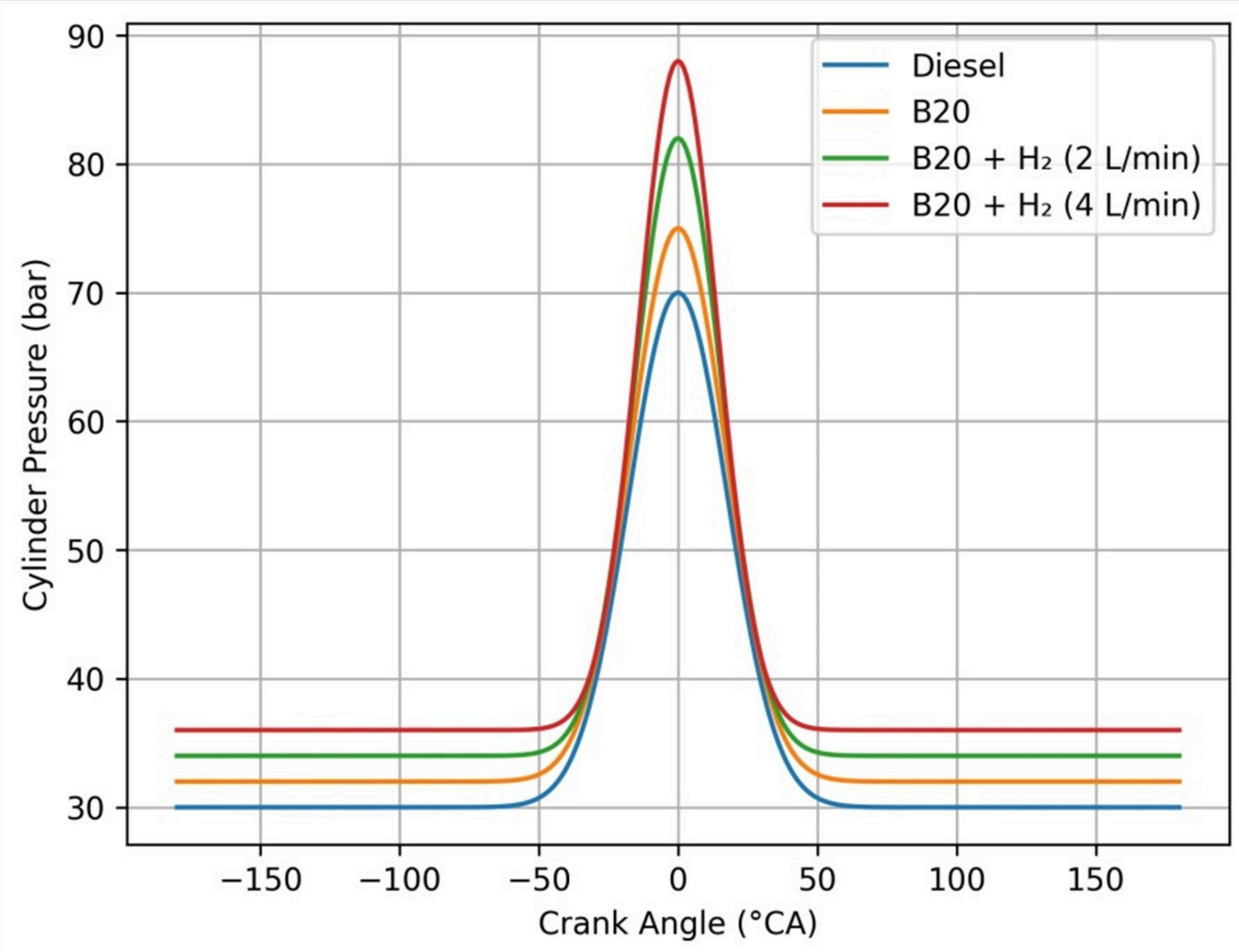

Figure 9

Variation of in-cylinder pressure with crank angle

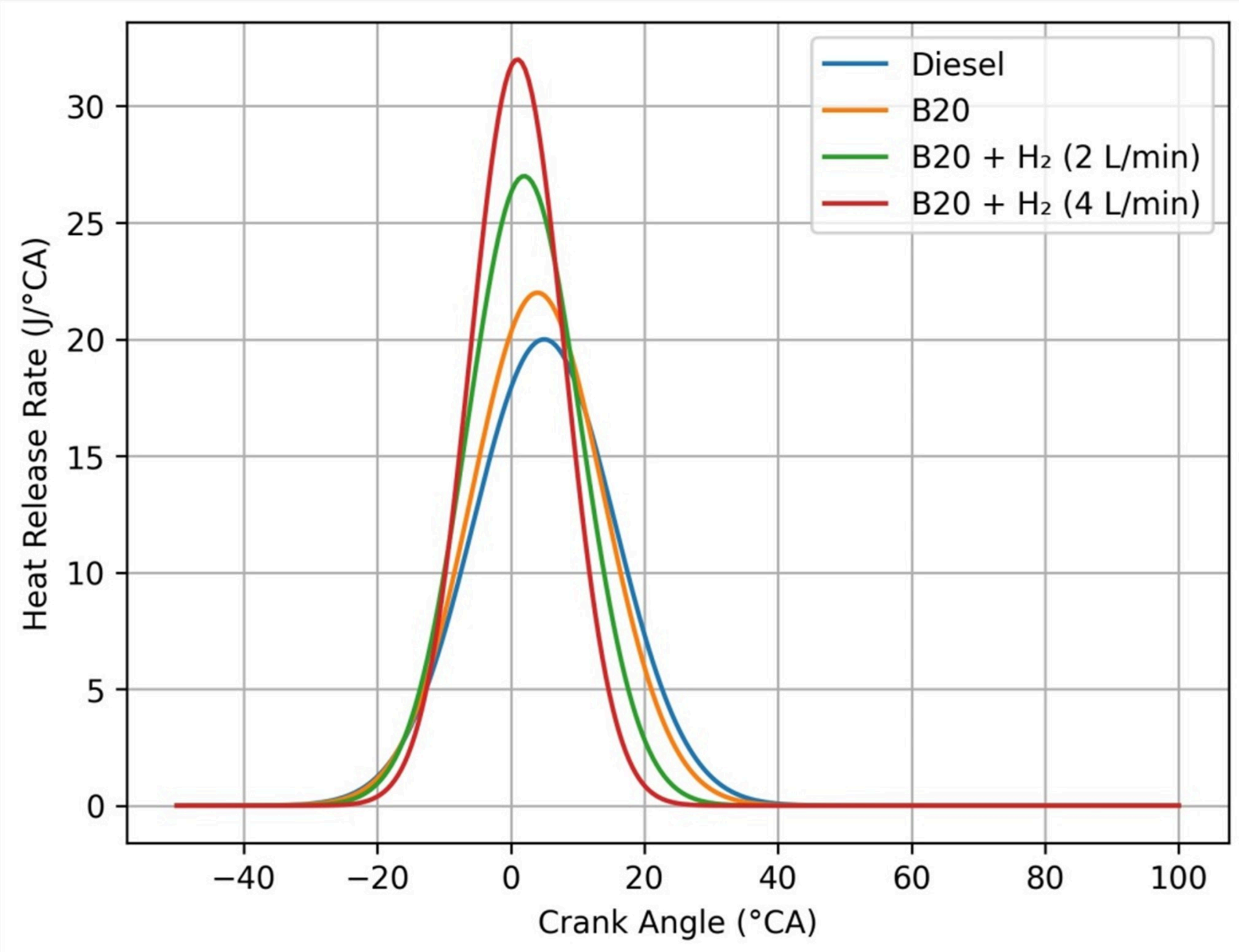

Figure 10

Variation of heat release rate (HRR) with crank angle