

Research Paper

Comprehensive analysis of CI engine attributes fuelled with oil mill waste oil-camphor oil blend with hydrogen enrichment—RSM approach

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ABSTRACT

This article aims to examine the significance of waste-to-energy principles concerning compression ignition engines. The article aimed to use a combination of oil mill waste oil and camphor oil with hydrogen enrichment. The central composite approach is used to construct two experimental matrices for the input parameters of load ranging from 50% to 100% and hydrogen flow rate from 0 to 10 LPM for two fuel types: oil mill waste oil (OM100) and a mix of oil mill waste oil and camphor oil (OMC50). The experiment is performed using a 4-stroke, water-cooled, computerized, single-cylinder compression ignition engine. ANOVA is used to assess the model (both linear and quadratic) and is deemed significant at a 95% confidence level. The incorporation of hydrogen at 10 LPM with OM100 enhances the BTE by 5.2%, EGT by 1.84%, BSNO by 8.08%, Acw by 30.71%, Aeg by 9.71%, SI by 3.79%, and ExE by 6.94%, while reducing the BSEC by 5.47%, BSCO by 17.98%, BSHC by 44.12%, BSCO₂ by 7.88%, smoke opacity by 10.84%, FE by 5.47%, Ad by 9.64%, EG by 9.64%, TEL by 35.98%, EnEL by 7.88%, and ExEL by 9.64% in comparison to OM100. Hydrogen additions at 10 LPM with OMC50 improve BTE by 5.2%, EGT by 1.62%, BSNO by 5.52%, Acw by 18.20%, Aeg by 11.54%, SI by 5.11%, and ExE by 8.36% while decreasing BSEC by 4.93%, BSCO by 28.88%, BSHC by 23.37%, smoke opacity by 5.99%, FE by 6.69%, Ad by 11.23%, TEL by 25.27%, EnEL by 8.37%, and ExEL by 11.23%.

1. Introduction

Biofuels from vegetable oils are an attractive sustainable alternative to fossil fuels for diesel engines (Aravind et al., 2025). Refined oils including castor oil, sesame oil, coconut oil, mahua oil, and rice bran oil are suitable for biodiesel manufacture and usage in CI engines because to their availability, renewability, and fuel properties (Saridemir et al., 2024; Abebe Debella et al., 2024). High viscosity and unique chemical composition of refined castor oil with linolenic acid are notable. Castor oil biodiesel performs similarly to diesel fuel but is biodegradable, non-toxic, and improves lubricity, extending engine life. Studies suggest

that 20% castor oil biodiesel blends to diesel improve performance and reduce emissions, making castor oil a promising CI engine feedstock. Sesame oil biodiesel's triglyceride concentration makes it like diesel. Studies suggest that sesame oil biodiesel may be utilized in CI engines without changes and function optimally at varying loads.

It is a good fuel in sesame-growing regions due to its renewable resources and combustion properties (Dinesha et al., 2019). Coconut Oil burns well in diesel engines due to its low viscosity and high cetane number. Biodiesel made from coconut oil has strong cold flow and a high carbon content, like diesel. Its clean-burning properties and tropical abundance make it ideal for CI engines (Rosiane de Almeida Andrade et al., 2024). Refined Mahua oil from arid-region seeds offers excellent

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Nomenclature

BTE	brake thermal efficiency
BSEC	brake specific energy consumptions
BSCO	brake specific carbon monoxide
BSCO ₂	brake specific carbon dioxide
BSNO	brake specific nitrogen monoxide
IC	internal combustion engine
CI	compression ignition engine
SI	spark ignition engine
ID	ignition delay
FE	fuel exergy
ExE	exergy efficiency
Ad-	deconstructed exergy
D	diesel

Aeg-	exhaust gas exergy
Acw	cooling water exergy
SOC	start of combustions
ExEL	exergoeconomic loss
TEL	Thermoeconomic loss
EnEL	Enviroeconomic loss
OM100	oil mill waste oil
OM100H5	oil mill waste oil with 5 LPM of hydrogen
OM100H10	oil mill waste oil with 10 LPM of hydrogen
OMC50	50% of oil mill waste oil + 50% of camphor oil
OMC50H5-	OMC50 + 5 LPM of hydrogen
OMC50H10	OMC50 + 10LPM of hydrogen
EG	Entropy generations
SI	sustainability index

oil output and diesel-like cetane number and calorific value. Alkaline transesterification of mahua oil produces biodiesel with minimal hydrocarbon, carbon monoxide, and nitrogen oxide emissions in CI engines. It is cheap and available, making it a potential alternative fuel in some areas (Dhairiyasamy and Gabiriel, 2025).

Another biodiesel fuel contender is refined rice bran oil, which has low viscosity and good oxidative stability. While less explored than other oils, rice bran oil biodiesel is a sustainable fuel suitable for CI engines, particularly when combined with diesel to enhance performance and emissions (Kanth et al., 2020; Mathan Raj et al., 2016). These five refined oils are diverse and sustainable biofuel feedstocks for CI engines. Each biofuel's viscosity, cetane number, availability, and environmental imprint allow for biofuel mixes that reduce fossil fuel consumption, emissions, and energy security across areas. Most investigations show that hydrogen intake at different flow rates with different biodiesels improves combustion performance, lowers bsfc, and reduces emissions. Hydrogen improves combustion characteristics (Thiyagarajan et al., 2022; Murugesan et al., 2022; Lalsangi et al., 2023a), irreversibility, and efficiency (Rawat et al., 2024; Taghavifar et al., 2021; Chaudhary et al., 2024).

Castro et al. (2019) found that hydrogen concentrations over the downward flammability limit caused backfire. Avoiding a backfire requires limiting hydrogen substitution below the flammability limit. They replaced up to 80% of gasoline energy with hydrogen without backfire at 30% engine load. At 60% load and 60% hydrogen energy, was near to the lower flammability limit. Beyond 70% hydrogen energy, knock intensity was higher at 100% and 60% load. Liu et al. (2021) devised a hydrogen-diesel dual injection to avoid knocking in traditional hydrogen engines. While preserving combustion timing, a CI engine with a hydrogen injector in the combustion cylinder reduces diesel input as hydrogen input increases. Premixed combustion is supported by early hydrogen injection, while mixing-controlled combustion is achieved later. The best engine settings were 47% indicated thermal efficiency, 50% hydrogen, 40° bTDC, 6 dB engine noise reduction, and NOx emissions below 11 g/kWh. Arumugam et al. (2024) examined soy (50–90%) and macauba (10–50%) methyl ester blends at varied speeds and loads, showing the effect of 5% hydrogen premixing. The addition of hydrogen to biodiesel from soy (80%) and macauba (15%) methyl ester reduced BSFC by 3% and improved BTE by 2.5%. Except NOx emissions have decreased at full load, suggesting improved combustion. Hydrogen reduced NOx emissions by 4.25 and 3.7% at low and high loads compared to 50% of biodiesels.

Thiagarajan et al., (2024) test the toroidal-type CI engine with hydrogen-assisted dual-fuel rapeseed + waste cooking oil). Biodiesel's oxygenated nature and hydrogen's fast-burning nature boosted

oxidation, decreased carbon emissions, and raised temperature, increasing NOx emissions. A mixture of 20% rapeseed oil, 70% diesel, and 10% waste cooking oil has a maximum BTE of 31.77% at heavy load, with hydrogen adding 3%. Kumar et al. (2022) examined Jatropa biodiesel fuel injection time and pressure with hydrogen intakes of 5, 7, and 9 lpm. Advanced timing and high injection pressure enhance premixed combustion. Low injection time reduced premix combustion and NOx emissions. A hydrogen flow rate of 9 L/min and pilot injection pressure of 1500 bar produced the maximum NOx emissions of 0.358 g/kWh. Zhang et al. (2022) developed a computational model to examine how hydrogen to biodiesel with various fatty acid methyl ester types influences marine diesel engine performance and emissions. At 6% hydrogen, cottonseed and rapeseed methyl esters showed 3.73% and 3.9% efficiency increases. All pollutants except NOx were greatly decreased by hydrogen.

A diesel engine was tested using 4 lpm of hydrogen, Jamun, diesel, and 5 and 10% ethanol by Ramalingam et al. (2023). Hydrogen, biodiesel, and ethanol synergistically reduce combustion time and increase engine performance. Hydrogen and biodiesel with ethanol have higher octane numbers and better combustion. The suction stroke mixes hydrogen with intake air, which burns fuel in the premixed stage to increase HRR and ICP. Additionally, ethanol's high vaporization energy cools and reduces NOx emissions in hydrogen-assisted ternary fuel mixes. Rajak et al. (2025) studied CI engine effects of hydrogen-ethanol blends using diesel R-K software. PM, fuel usage, and smoke emissions decreased with every load and hydrogen %. However, mixture formation and flame speed increase NOx generation. Pachiannan et al. (2025) investigated enriching diesel with n-pentanol using double injection and 4 LPM hydrogen in a CI engine. Advanced timings increase combustion phasing, increasing energy conversion efficiency and minimizing all pollutants except NOx. Hydrogen enrichment reduces n-pentanol combustion problems, improving engine performance and pollution. According to Rawat et al. (2023), adding hydrogen and injecting it for 2500 ms further increases energy and energy efficiency while lowering energy losses and entropy formation, all while maintaining the same emissions trends.

Chaichan et al. (2018) found that 100% sunflower oil biodiesel with EGR and hydrogen induction reduces NOx emissions. EGR delayed combustion and temperature, resulting in hot and cooled EGR 14% and 16% at the rated speed. However, EGR increases exhaust carbon emissions. Vellaiyan (2025) optimized using 50 g/h hydrogen, 30% cotton seed biodiesel, and 15% EGR. The best engine performance-emission reduction trade-off is 20.17% CSB, 26.99 g/h hydrogen flow rate, and 5.37% EGR. The maximum NOx reduction under optimum settings was 44.3% lower than without EGR. Bhawe et al. (2022) found PCCI struggles

to reduce CO and HC emissions. Oxy hydrogen gas was added to the fuel mix to solve this problem. A normal diesel engine was converted to PCCI mode with port fuel injection and hot air. Oxy hydrogen increased engine efficiency and pressure due to quick burning. It significantly reduced CO and HC emissions, especially at half loads, without increasing NOx or smoke. Despite not recirculating exhaust gas, emissions were minimal. H et al. (2025) tested 20% Dunaliella salina microalgae in diesel with 2–6 lpm hydrogen induction. Due to its low calorific value, biodiesel has a lower mean gas temperature and lower smoke emissions than diesel. Due to its non-sooting, thermally and chemically homogeneous reaction zone, hydrogen minimizes smoke emissions and enhances fuel mix combustion.

Bayramoglu et al. (2025) under low load, the destruction of exergy was observed to be higher. However, from low torque to maximum torque, hydrogen induction of 40 LPM using a dual fuel blend (80% WCO and 20% diesel) enhances the fuel exergy by 180%, stemming through improved combustion efficiency and higher energy release. The peak first and second law efficiencies were recorded at 30.5% and 28.5%, respectively, at 75% of load, owing to better combustion efficiency. In a CI engine, these results demonstrate the potential for improved thermodynamic performance and less environmental impact through the use of low-viscosity biofuels or oxygenated fuels in alternative dual-fuel combinations. Wategave et al. (2025) modified a CI engine to operate under RCCI mode using hydrogen-enriched CNG and hydrogen (H₂) with diesel–Karanja biodiesel to enhance emission cleanliness. The HC and CO pollutants were found to be lower for hydrogen with biodiesel compared to hydrogen-enriched CNG. The HC pollutants was observed 138 ppm for hydrogen-enriched CNG, while CO emissions dropped to 0.02% for increasing the energy share of biodiesel.

Similarly, Lalsangi et al. (2023b) experimented dairy scum and waste frying biodiesels using constant flow rate of hydrogen-enriched producer gas. The findings indicated elevated NO pollutants associated with lesser viscosity of dairy scum biodiesel, which atomises more readily and enhances the rate of heat release due to its superior ignition quality and calorific value. B et al. (2024) examined the synergistic effect of hydrogen and 20% of Calophyllum inophyllum biodiesel with diesel to control NOx emission under an altered compression ratio (15.5). At a CR15.5, an average NOx reduction of 24.6% was noted, which is stemming from the lower temperature combustion.

This article study about the comparative performance of five distinct biofuels blends such as refined castor oil, sesame oil, coconut oil, refined Mahua oil, and refined rice bran oil as base fuels in hydrogen-assisted dual-fuel diesel engine operation. Unlike conventional studies mostly focused on single or limited ternary mixtures of biodiesel with hydrogen, this approach provides in-depth knowledge of the synergistic effects of hydrogen addition on a well-distributed feedstock selection with different chemical compositions and burning characteristics. The research presents new insights towards the optimization of dual-fuel strategies by exploring fuel-specific benefits and compromises, thus supporting flexible, region-specific, and sustainable energy solutions for compression ignition engines.

Waste oil containing five different biofuels is collected from the oil mill, and the same has been used to study the CI engine attributes. Despite the existence of literature that separately studies CI engine attributes, the study focuses on the CI engine attributes of the five biofuel combinations. Researchers put in significant effort to convert these oils into biodiesel and test it in CI engines. Even after a reduction in viscosity, literature is not recommending the 100% substitution of biodiesel, and it is recommending the 20–30% replacement of diesel fuel. Thus, research attempts to address high viscosity issues by combining clean gaseous fuels with low viscosity biofuel, which has a lower cetane rating. Gaseous fuel with a greater reactivity may speed up combustion and improve energy transfer, resulting in increased efficiency. Thus, this research uses waste oils from oil mills to investigate how adding hydrogen and camphor oil affects the characteristics of CI engines.

2. Expressions

2.1. Fuel exergy

$$FE = m_f \bullet CV \bullet \left[1.041 + 0.1728 \left(\frac{H}{C} \right) + 0.0432 \left(\frac{O}{C} \right) \right] \quad (1)$$

Where

mf – fuel consumptions in kg/s, CV – lower heating value in kJ/kg, FE – fuel exergy in kW.

2.2. Useful exergy rate

$$A_{\text{useful}} = BP \quad (2)$$

Where BP – brake power in kW

2.3. Cooling water exergy rate

$$A_{\text{cw}} = \left\{ (m_{\text{cw}} \bullet C_{\text{cw}} (T_{\text{cwo}} - T_{\text{cwi}})) - \left(m_{\text{cw}} \bullet C_{\text{cw}} \bullet T_{\text{amb}} \bullet \frac{T_{\text{cwo}}}{T_{\text{cwi}}} \right) \right\} \quad (3)$$

Where Acw – cooling water exergy in kW, Mcw – flow rate of engine cooling water in kg/s, Ccw- specific heat of cooling water in kJ/kgK, Tamb – ambient temperature in K, Tcwo – cooling water outlet temperature in K, Tcwi – cooling water inlet temperature in K.

2.4. Exhaust gas exergy rate

$$A_{\text{eg}} = (m_{\text{eg}} \bullet C_{\text{eg}} \bullet (T_{\text{eg}} - T_{\text{amb}})) - \left(m_{\text{eg}} \bullet T_{\text{amb}} \bullet \left(C_{\text{Peg}} \bullet \ln \frac{T_{\text{amb}}}{T_{\text{eg}}} - R_{\text{eg}} \bullet \ln \frac{P_{\text{amb}}}{P_{\text{eg}}} \right) \right) \quad (4)$$

Where

Aeg – exhaust gas flow rate in kg/s, Teg – exhaust gas temperature in K, CPeg – specific heat of exhaust gas in kJ/kgK, Reg – gas constant in kJ/kgK, Pamb – ambient pressure in bar, Peg – exhaust gas exit pressure in bar.

2.5. Destructed exergy rate

$$A_d = FE - A_{\text{useful}} - A_{\text{cw}} - A_{\text{eg}} \quad (5)$$

Where

Ad – destructed exergy in kW

2.6. Entropy generation

$$EG = \frac{A_d}{T_{\text{amb}}} \quad (6)$$

Where, EG – entropy generation in kW/K

2.7. Exergy efficiency

$$ExE = 1 - \frac{A_d}{FE} \quad (7)$$

Where ExE – exergy efficiency in %

2.8. Sustainability index

$$SI = 1 - \frac{1}{ExE} \quad (8)$$

Where SI – sustainability index

2.9. Energy loss

$$E_{loss} = Qi - BP - Q_{eg} \quad (9)$$

Where Eloss – energy loss in kW, Qi – heat input in kW, Qeg – heat loss in engine exhaust in kW

2.10. Thermoeconomic loss

$$TEL = \frac{E_{loss}}{EC} \quad (10)$$

Where TEL – thermoeconomic loss in kW/\$, EC – Equipment cost in \$

2.11. Exergy loss

$$Ex_{loss} = E_{loss} \cdot \left(1 - \frac{T_{amb}}{T_{cw}}\right) \quad (11)$$

Where Exloss – exergy loss in kW

2.12. Exergoeconomic loss

$$ExEL = \frac{A_d}{EC} + \frac{Ex_{loss}}{EC} \quad (12)$$

Where ExEL – exergy loss in kW/\$

2.13. Enviroeconomic loss

$$EnEL = BSCO_2 \times BP \times H \times \text{cost of CO}_2 \quad (13)$$

Where EnEL – enviroeconomic loss in \$/day.

3. Materials and methods

3.1. Materials

Oil mill waste oil is purchased from the local oil mill available in Tamil Nadu, India. Camphor oil and hydrogen were procured from the supplier from Tamil Nadu, India. The fuel properties of the raw oil and fuel blends are tested using the facilities available in the thermal laboratory in a university lab. ASTM D240, D445, D1298, and D93 standards are used to measure lower heating value, kinematic viscosity, density, and flash point using a Bomb calorimeter, Redwood viscometer, hydrometer, and Pensky-martens apparatus (Table 1).

3.2. Experimental test matrix

The experiment is conducted by a single fuel mode with diesel, 100% oil mill waste oil, and a binary blend containing 50% oil mill waste oil and camphor oil. When the engine is operated on 100% oil mill waste oil and then a binary fuel consisting of oil mill waste oil and camphor oil, hydrogen flows at 5–10 LPM in dual fuel mode (Table 2).

3.3. Engine test rig

An eddy-type dynamometer and a 4-stroke computerized single-

Table 1
fuel properties.

Fuel properties	Oil mill waste oil	hydrogen	diesel	Camphor oil
Stoichiometric air fuel ratio	12.94	32	14.9	12.6
Density (kg/m ³)	920	0.089	830	894
Stoichiometric oxygen -fuel ratio	2.97	8	3.42	2.30
Viscosity 40 °C (cST)	33	-	4	2.5
Lower heating value (kJ/kg)	38600	120000	42500	38200
% of carbon	78.26	0	85.71	80.54
% of hydrogen	12.32	100	14.29	10.74
% of oxygen	9.42	0	0.00	8.72
Carbon/hydrogen	0.53	0	0.50	0.63

Table 2
Test matrix.

Fuel name	Fuels details
OM100	Oil mills waste oil
OM100H5	Oil mill waste oil + 5 LPM of hydrogen
OM100H10	Oil mill waste oil + 10 LPM of hydrogen
OMC50	Equally blended Oil mill waste oil and camphor oil
OMC50H5	Equally blended Oil mill waste oil and camphor oil + 5 LPM of hydrogen
OMC50H10	Equally blended Oil mill waste oil and camphor oil + 10 LPM of hydrogen

cylinder direct injection compression ignition engine are used in the experiment (refer Fig. 1). The mass flow rate of the air and volumetric efficiency are determined by measuring the airflow rate in a water column using an airflow transmitter. The K-type thermocouple is used to record the cooling water temperatures at the intake and outflow. A K-type thermocouple is used to measure the exhaust gas temperature as it exits the tailpipe. With an eddy current dynamometer, loads operating on the engine are recorded using a load cell and its indication. The speed and crank angle positions are recorded with the help of a crank angle encoder attached to the crankshaft of the engine. Differential pressure transmitters are used to find the fuel flow rate. We use gas analyzers and smoke meters to record the emissions from the engine. Through a pressure regulator, hydrogen is transferred from the hydrogen cylinder to the engine cylinder. For safety reasons, a wet flame arrestor and a flashback or dry flame arrestor are connected between the engine manifold and the hydrogen cylinder, particularly to stop backfires (Table 3).

A hydrogen rotameter is used to measure the flow rate of the hydrogen supplied to the engine through the inlet manifold along with air. Experiments are conducted by maintaining the steady-state conditions (the engine is allowed to run for 20 min before the commencement of the experiments). Each trial is repeated three times, and the average is used for the calculations. The hydrogen flow rate is gradually increased through the hydrogen rotameter when the engine is running at full load. After reaching the 10 LPM of hydrogen supply, the functioning of the engine slightly deviated from the normal behavior (experienced from the variations of the sound of the engine). Therefore, the maximum limit of the hydrogen supply is stopped at 10 LPM. Brake-specific emissions are calculated using the following equations.

$$BSCO = \frac{CO_{in} \% \cdot \text{Molecular weight of CO} \cdot (Mass_{air} + mass_{fuel}) \cdot 3600 \cdot 1000}{\text{molecular weight of exhaust gas} \cdot 100 \cdot \text{Brake power}} \quad (14)$$

$$BSHC = \frac{HC_{in ppm} \cdot \text{Molecular weight of HC} \cdot (Mass_{air} + mass_{fuel}) \cdot 3600 \cdot 1000}{\text{molecular weight of exhaust gas} \cdot 1000000 \cdot \text{Brake power}} \quad (15)$$

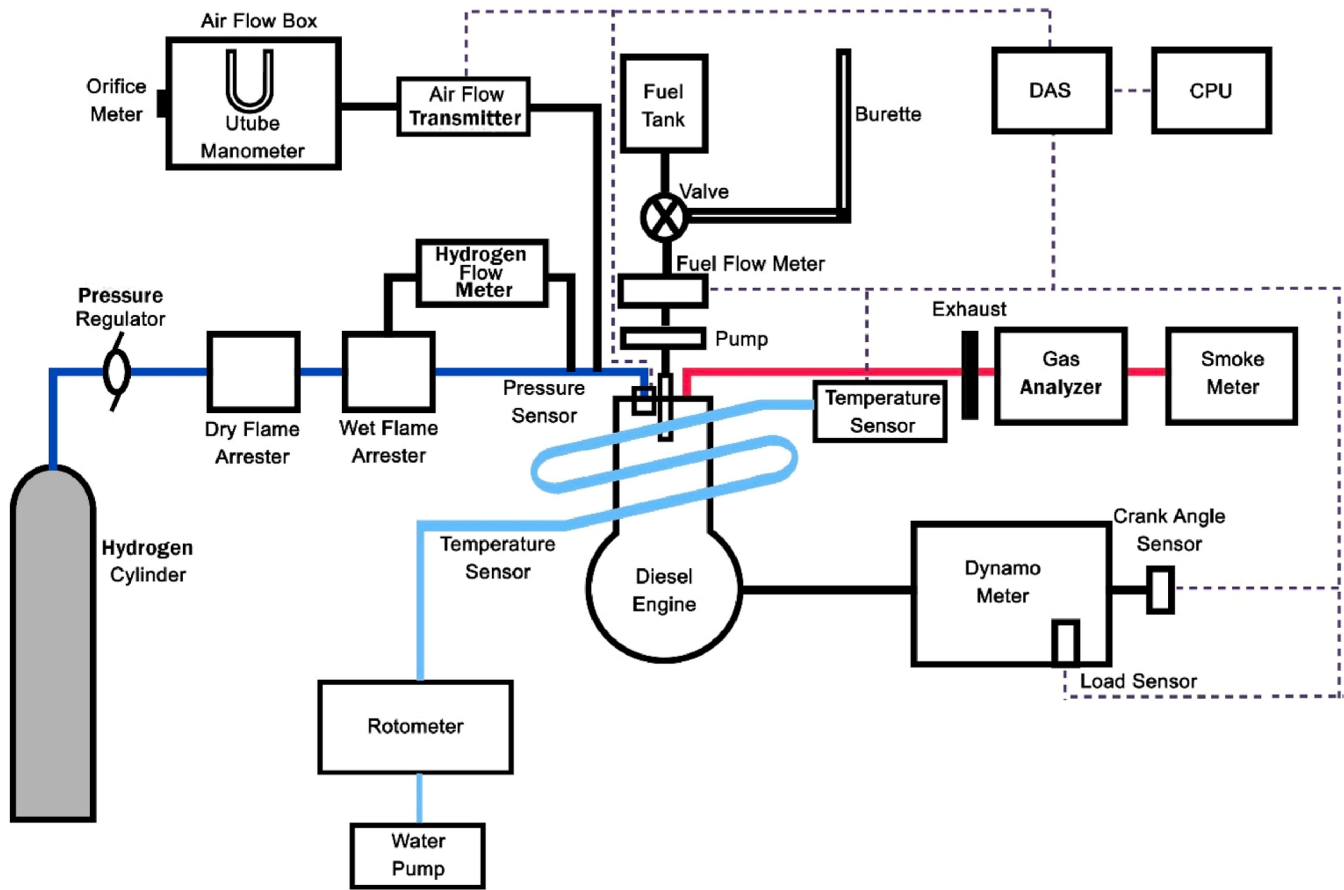


Fig. 1. schematic diagram of the test rig.

Table 3
Test rig details.

Descriptions	Specifications
Bore x stroke, compression ratio, Clearance volume, swept volume	87.5 mm × 110 mm, 17.5, 40 cm ³ , 661 cm ³ .
Model, Make, number of cylinder and stroke.	TV1, Kirloskar, 1 and 4.
Type of injections	Solid injection systems and direct injection systems
Injection pressure and timing	200 bar and 23 °CA bTDC
Dynamometer	Eddy current dynamometer
Load sensor	Strain Gauge, range 0–50 kg
Temperature	K- type RTD range: 1200 °C, accuracy ±0.1 °C
Crank angle encoder	TDC type, Accuracy ±0.1%
Air flow transmitter	Range ± 250 mm, differential type
Rotameter	Ball type; range: 40–400 LPH
Fuel flow transmitter	Pressure differential type
Gas analyzer	Make: AVL 444 N digas analyser
NO	resolution of 1 ppm; Electrochemical; Range: 0–5000 ppm; accuracy ± 5 ppm
CO	resolution of 0.01% vol; NDIR; Range: 0–10% vol, accuracy ± 0.02%
HC	resolution of 1 ppm; NDIR; Range: 0–20000 ppm; accuracy ± 8 ppm
CO ₂	NDIR; Range: 0–20% vol; accuracy ± 3% by vol
Smoke meter	AVL 437 C smoke meter
Smoke	resolution 0.1%; Range: 0–100%; Accuracy - ±1%

$$BS_{CO_2} = \frac{CO_{2in \%} \bullet \text{Molecular weight of } CO_2 \bullet (Mass_{air} + mass_{fuel}) \bullet 3600 \bullet 1000}{\text{molecular weight of exhaust gas} \bullet 100 \bullet \text{Brakepower}} \quad (16)$$

$$BS_{NO} = \frac{NO_{in ppm} \bullet \text{Molecular weight of } NO \bullet (Mass_{air} + mass_{fuel}) \bullet 3600 \bullet 1000}{\text{molecular weight of exhaust gas} \bullet 1000000 \bullet \text{Brakepower}} \quad (17)$$

3.4. Uncertainty of the experiment

Uncertainty of the experiment delineates the percentage of error that occurs during the experiments that relies on observation error and instrumental errors. Uncertainties of the presented model is taken from the model proposed by [Duraisamy et al. \(2019\)](#) and [Edara et al. \(2018\)](#). Based on 3 trials of reading, the mean and standard deviation are calculated and used to determine the observed error. Average and standard deviations of the three trails are calculated using [Eqs. 18 and 19](#). [Eq. 20](#) is used to find the uncertainty of the observed error of each

Table 4
uncertainty of experiment for each variable.

Parameter	observation			U95%	IE	Uncertainty (%)
	1	2	3			
CO	0.276	0.278	0.276	0.68	0.02	0.68
smoke	70.06	70.16	70.58	0.641	0.1	0.65
HC	101.5	102	102.5	0.800	0.1	0.81
NO	1830	1840	1845	0.6784	0.2	0.71
CO ₂	4.78	4.8	4.83	0.855	0.2	0.88
EGT	398	400	401	0.624	0.1	0.63
BTE	31.3	31.55	31.45	0.653	0.5	0.82
BSEC	11.5	11.46	11.4	0.717	0.5	0.87
VE	74	74.5	74.75	0.837	0.1	0.84
ICP	73	73.5	73.65	0.757	0.1	0.76
HRR	43.5	43.36	43.26	0.453	0.1	0.46
ROPR	3.26	3.25	3.28	0.764	0.1	0.77
EE	38.45	38.65	38.58	0.429	0.5	0.66
overall uncertainty						± 2.68

variable for the confidence level of 95%. Eq. 21 is used to determine the uncertainty of each variable, and Eq. 22 is used to find the uncertainty of the experiment (Table 4).

$$\mu = \frac{\sum_{i=1}^n x_i}{n} \quad (18)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \mu)^2}{n}} \quad (19)$$

$$\text{Each parameter's Uncertainty } (U_{95})\% = \frac{2\sigma}{\mu} \times 100 \quad (20)$$

$$\text{Uncertainty of each variable} = \sqrt{(U_{95})\%^2 + IE^2} \quad (21)$$

Where,

σ - standard deviation of each parameter

μ - mean of each parameter

$$\text{Overall uncertainty of the experiment} = \sqrt{CO^2 + smoke^2 + HC^2 + NO^2 + CO_2^2 + EGT^2 + BTE^2 + BSEC^2 + VE^2 + ICP^2 + HRR^2 + ROPR^2 + EE^2} \quad (22)$$

3.5. Response surface methodology models

Using regression equations, the response surface approach is a statistical method that is used to determine the relationship between the independent variables and the interaction on the output response. ANOVA was used to analyze the statistical model, and the level of confidence was increased to 90 % (Singh et al., 2021). The linear and quadratic models are formed for the response. The model obtained for the response agrees with the 95% confidence level. The Table 5, Table 6, Table 7 and Table 8 gives the details of the statistical model formed for the response. The p-value for all the formed values found a 5% error level. The R² values of TEL, ExEL, EnEL, BTE, BSEC, BSCO, BSHC, BSCO₂, BSNO, smoke opacity, FE, Acw, Ad, EG, ExE, SI, VE, and EGT for the first experimental matrix are 0.9941, 0.9991, 1, 1, 0.9961, 0.9791, 0.9995, 0.9994, 0.9762, 1, 0.9759, 0.9590, 0.9999, 0.9999, 0.9993, 0.9940, 0.9890, and 0.9988, respectively. TEL, ExEL, EnEL, BTE, BSEC, BSCO,

BSHC, BSCO₂, BSNO, smoke opacity, FE, Acw, Ad, EG, ExE, SI, VE, and EGT for the second experimental matrix are 0.9991, 0.9999, 1, 1, 1, 0.9770, 0.9758, 0.9995, 0.9996, 0.9870, 1, 0.9608, 0.9982, 0.9999, 0.9999, 0.9999, 0.9999, 0.9980, and 0.9997, respectively. These R² values fall within the 95% confidence level, indicating that the statistical model developed based on the first and second experimental matrices are reliable, standard, and within acceptable limits. With a 90% confidence level, Aytav (2024) assessed the ANOVA model for an R² value between 0.90 and 0.99. Musthafa and Asokan (2024) assessed the RSM model with an R² value between 0.9881 and 0.9984, which is consistent with our model's findings at the 95% confidence level. The findings that were mentioned above provide evidence that our R² coincides with the independent factors and the output response.

4. Results and discussion

4.1. Performance characteristics

4.1.1. Brake thermal efficiency

BTE is the parameter used to find how much of fuel energy is turned into the engine's usable output. It depends on how the fuel goes through an exothermic reaction and sends power to the engine shaft during cyclic processes.

4.1.1.1. Impact of hydrogen addition on thermal efficiency using oil mill waste oil. Fig. 2 illustrates the changes in BTE related to the collaboration between load and hydrogen premixing rate. The BTE was obtained for Diesel, OM100, OM100H5, OM100H10 is 30.95%, 28.02%, 28.79% and 29.56% from the obtained value the BTE for OM100H10 is increased around 5.2% compared to OM100 and 2.6% compared to OM100H5. OM100 has a poorer brake thermal efficiency because to the slower combustion dynamics associated with the ignition of bigger fuel droplets, which is a consequence of heightened viscosity. The aforementioned reading verifies that the incorporation of hydrogen gas has a favorable outcome in BTE. The increased diffusivity of hydrogen enables its distribution throughout the combustion chamber, mostly on the upper side, owing to its reduced density. Conversely, liquid fuel may reside at the base of the combustion chamber, facilitating uniform combustion. The rapid combustion characteristics of hydrogen facilitate ignition during the uncontrolled combustion phase, hence improving

energy transmission to the piston. Increased flame speed and temperature result in enhanced temperature and pressure of combustion products, facilitating heat and energy transmission while expediting the oxidation process. Rahman (2019) articulated that the participation of hydrogen at 10 LPM with 40% algae biodiesel-blended diesel fuel boosts the thermal efficiency by 7.5%, which is in line with current results.

4.1.1.2. Impact of hydrogen induction on thermal efficiency oil mill waste oil-camphor oil blend. Fig. 3 shows how the BTE changes when the hydrogen premixing rate and load interact in an oil mill waste oil-camphor oil combination. The BTE was obtained for Diesel, OM100, OC50, OC50H5, OC50H10 is 30.95%, 28.02%, 31.04%, 31.85% and 32.65% from the obtained value the BTE for OC50H10 is increased around 5.2% compared to Diesel and 14.2% compared to OM100. OMC50 has a superior brake thermal efficiency (BTE) compared to OM100, attributable to the advantageous influence of reduced viscosity.

Table 5
ANOVA details for oil mill waste oil.

Parameter	mean	Std dev	CV	Mean square	F- value	Sum of square	R ²	Adj R ²
TEL	0.0010	0.0000	2.08	1.302E-07	281.65	3.906E-07	0.9941	0.9906
ExEL	0.0020	4.861E-06	0.2397	2.532E-07	10715.58	1.266E-06	0.9999	0.9999
EnEL	0.3910	0.0090	2.30	0.0453	561.88	0.0906	0.9947	0.9929
BTE	27.07	0.0194	0.0716	6.33	16862.80	31.66	1.0000	0.9999
BSEC	13.37	0.0109	0.0815	1.65	13935.07	8.27	1.0000	0.9999
BSCO	14.83	0.7270	4.90	80.86	152.98	404.29	0.9961	0.9896
BSHC	0.5747	0.0265	4.61	0.0203	28.91	0.1015	0.9797	0.9458
BSCO ₂	924.20	2.16	0.2339	5278.55	1129.22	26392.73	0.9995	0.9986
BSNO	9.60	0.0221	0.2305	0.5101	1041.47	2.55	0.9994	0.9985
SMOKE	72.22	1.96	2.72	474.27	123.01	948.54	0.9762	0.9683
FE	15.08	0.0056	0.0371	19.21	6.124E + 05	96.06	1.0000	1.0000
Acw	0.8906	0.0339	3.80	0.1396	121.53	0.2791	0.9759	0.9679
Aeg	5.83	0.1942	3.33	2.65	70.25	5.30	0.9590	0.9454
Ad	10.14	0.0243	0.2397	6.33	10715.58	31.64	0.9999	0.9999
EG	0.0338	0.0001	0.2397	0.0001	10715.58	0.0004	0.9999	0.9999
ExE	32.26	0.1187	0.3680	12.63	896.33	63.14	0.9993	0.9982
SI	1.48	0.0024	0.1621	0.0059	1034.30	0.0297	0.9994	0.9985
VE	79.93	0.2578	0.3225	9.94	149.58	29.81	0.9890	0.9824
EGT	572.85	3.60	0.6283	6683.35	515.90	33416.75	0.9988	0.9969

Table 6
Equations and model details for oil mill waste oil.

Parameter	Model equation	P- value	Model type
TEL	TEL = 0.000462 + 9.64211E - 06 * LD - 7.52386E - 06 * H - 3.02903E - 07 * LD * H	< 0.0001	Linear
ExEL	EnEL = 0.035504 + 0.004893 * LD - 0.002299 * H ExEL = 0.001020 + 9.61226E - 06 * LD - 4.25011E - 06 * H - 1.93168E - 07 * LD * H + 6.22671E - 08 * LD ² + 9.98505E - 08 * H ²	< 0.0001	Quadratic
ExE	ExE = 16.10955 + 0.297437 * LD + 0.161224 * H + 0.000753 * LD * H - 0.001206 * LD ² + 0.000846 * H ²	< 0.0001	Quadratic
EG	EG = 0.017003 + 0.000160 * LD - 0.000071 * H - 3.21946E - 06 * LD * H + 1.03779E - 06 * LD ² + 1.66417E - 06 * H ²	< 0.0001	Quadratic
Aeg	Aeg = 2.85820 + 0.035757 * LD + 0.058048 * H	< 0.0001	Linear
Ad	Ad = 5.10086 + 0.048061 * LD - 0.021251 * H - 0.000966 * LD * H + 0.000311 * LD ² + 0.000499 * H ²	< 0.0001	Quadratic
Acw	ACW = 0.296096 + 0.005797 * LD + 0.031949 * H	< 0.0001	Linear
SI	SI = 1.15780 + 0.005692 * LD + 0.002142 * H + 0.000034 * LD * H - 0.000022 * LD ² + 0.000028 * H ²	< 0.0001	Quadratic
FE	FE = 5.70842 + 0.092124 * LD - 0.021087 * H - 0.000849 * LD * H + 0.000475 * LD ² + 0.000429 * H ²	< 0.0001	Quadratic
Smoke opacity	Smoke opacity = 42.80556 + 0.460000 * LD - 1.01667 * H	< 0.0001	Linear
BSHC	BSHC = 1.60613 - 0.024402 * LD - 0.011011 * H + 0.000106 * LD * H + 0.000147 * LD ² - 0.001820 * H ²	0.0097	Quadratic
BSNO	BSNO = 9.04069 + 0.037177 * LD + 0.023109 * H + 0.000218 * LD * H - 0.000410 * LD ² + 0.001223 * H ²	< 0.0001	Quadratic
BSCO ₂	BSCO ₂ = 1063.51918 - 5.13175 * LD - 10.26626 * H + 0.016750 * LD * H + 0.047240 * LD ² + 0.124850 * H ²	< 0.0001	Quadratic
BSCO	BSCO = 56.22795 - 1.49554 * LD - 0.043569 * H - 0.003774 * LD * H + 0.011928 * LD ² + 0.008131 * H ²	0.0008	Quadratic
EGT	EGT = 474.72861 - 0.748567 * LD + 1.40650 * H + 0.001140 * LD * H + 0.024669 * LD ² - 0.053867 * H ²	0.0001	Quadratic
VE	VE = 88.10093 - 0.102595 * LD - 0.344037 * H + 0.003312 * LD * H	< 0.0001	2FI
BTE	BTE = 11.16725 + 0.342854 * LD + 0.110950 * H + 0.000445 * LD * H - 0.001744 * LD ² + 4.96557E - 07 * H ²	< 0.0001	Quadratic
BSEC	BSEC = 22.09232 - 0.190406 * LD - 0.092080 * H + 0.000226 * LD * H + 0.000979 * LD ² + 0.000380 * H ²	< 0.0001	Quadratic

Moreover, a reduced cetane rating facilitates more efficient combustion of the fuel, resulting in enhanced energy transfers. Consequently, OMC50 exhibits superior thermal efficiency compared to OM100. The inclusion of hydrogen in OMC50 facilitates the examination of the fuel combustion rate during the uncontrolled combustion phase. The advantageous chemical properties of hydrogen, including increased diffusivity and enhanced reactivity with camphor oil, expedite the combustion process. The rapid flame velocity and elevated temperature enhance the combustion rate of OMC50. Indeed, it enhances energy transmission and elevates the BTE. Based on the combustion product of hydrogen (formation of water vapor), Nicolas [Castro et al. \(2019\)](#) noted the drop in fuel conversion while inducing the hydrogen with diesel fuel. Formed water vapour has the tendency to absorb the heat released by the combustion process; as a consequence, it abates the BTE, which is not in line with the present BTE outcome. "The dealings of hydrogen (15 LPM flow rate) with cashewnut shell biodiesel-diesel blend blending ratio maximum of 30%) in a CI engine heighten the BTE", stated by [Hariharan et al. \(2019\)](#) which is aligned with current results.

4.1.2. Brake specific energy consumption

Brake specific energy consumption conveys how much fuel energy is effectively used to convert into useful oil.

4.1.2.1. Impact of hydrogen induction with oil mill waste oil on brake specific energy consumption. [Fig. 4](#) illustrates the changes in BSEC related to the collaboration between load and hydrogen premixing rate. The BSEC was obtained for Diesel, OM100, OM100H5, OM100H10 is 11.62%, 12.85%, 12.50% and 12.18% from the obtained value the BSEC for OM100H10 is increased around 4.5% compared to Diesel. OM100 has the greatest BSEC due to an inefficient energy conversion process resulting from sluggish and incomplete combustion, attributed to inadequate atomization caused by elevated viscosity. The increased viscosity of OM100 worsens air-fuel mixtures, resulting in suboptimal energy release rates that impair energy transmission. The inclusion of hydrogen impairs breathing capacity and displaces air molecules, potentially hindering oxidation processes. Consequently, it may result in suboptimal BSEC. Conversely, the elevated reactivity and diffusivity of hydrogen may significantly engage in all phases of combustion, including the afterburning phase, so facilitating energy transfer and delivering more energy to the pistons. Consequently, the introduction of hydrogen up to 10 LPM diminishes the BSEC.

4.1.2.2. Impact of hydrogen induction with oil mill waste oil – camphor oil blend on brake specific energy consumption. The [Fig. 5](#) illustrates the changes in BSEC related to the collaboration between load and hydrogen premixing rate for oil mill waste oil-camphor oil blend. The BSEC was

Table 7

ANOVA Details For Oil Mill Waste Oil- Camphor Oil Blend.

Parameter	mean	Std dev	CV	Mean square	F- value	Sum of squares	R2	Adj R2
TEL	0.0007	7.163E-06	1.05	3.253E-08	634.04	1.627E-07	0.9991	0.9975
ExEL	0.0018	6.342E-06	0.3616	1.867E-07	4642.08	9.335E-07	0.9999	0.9997
EnEL	0.3699	0.0006	0.1693	0.0246	62693.82	0.1229	1.0000	1.0000
BTE	29.94	0.0203	0.0680	7.67	18526.34	38.36	1.0000	0.9999
BSEC	12.08	0.0093	0.0774	1.34	15322.35	6.69	1.0000	0.9999
BSCO	11.47	1.20	10.51	37.02	25.51	185.09	0.9770	0.9387
BSHC	0.2797	0.0098	3.49	0.0023	24.23	0.0115	0.9758	0.9356
BSCO ₂	837.53	1.88	0.2247	4294.31	1212.03	21471.56	0.9995	0.9987
BSNO	10.73	0.0215	0.2006	0.6895	1487.96	3.45	0.9996	0.9989
SMOKE	62.90	1.75	2.78	698.66	228.24	1397.31	0.9870	0.9827
FE	13.72	0.0255	0.1860	16.03	24607.18	80.14	1.0000	0.9999
Acw	1.28	0.0401	3.14	0.1182	73.63	0.2364	0.9608	0.9478
Aeg	6.19	0.0580	0.9368	1.09	324.44	5.46	0.9982	0.9951
Ad	8.77	0.0317	0.3616	4.67	4642.08	23.34	0.9999	0.9997
EG	0.0292	0.0001	0.3616	0.0001	4642.08	0.0003	0.9999	0.9997
ExE	35.55	0.0356	0.1003	15.20	11963.01	76.00	0.9999	0.9999
SI	1.55	0.0012	0.0774	0.0087	6019.01	0.0436	0.9999	0.9997
VE	81.60	0.1246	0.1527	12.91	831.73	38.73	0.9980	0.9968
EGT	564.32	1.77	0.3131	6028.27	1930.65	30141.37	0.9997	0.9992

obtained for Diesel, OM100, OC50, OC50H5, OC50H10 is 11.62%, 12.84%, 11.59%, 11.30% and 11.02% from the obtained value the BSEC for OC50H10 is decreased around 5.4% compared to Diesel and 16.5% compared to OM100. As a result of the increased atomization that is brought about by the reduced viscosity of camphor oil, OMC50 exhibits a lower BSEC in comparison to OM100. In addition, the lower cetane rating of camphor oil allows fuel to accumulate and burn in the early stages of the combustion process, which increases the likelihood of turbulence occurring during the combustion process. waiting time that was stretched out. This results in an increase in energy exchanges, which in turn lowers the BSEC. In the presence of OMC50, combustion processes are sped up as a result of the existence of instant rapid combustion behavior, greater diffusivity and homogeneity, faster flame speed, higher flame temperature, and a wide range of flammability. Due to the greater heating value of the hydrogen, [Subburayalu Ramesh and Thiagarajan \(2024a\)](#) observed a drop in BSEC, which is consistent with the current BSEC data.

4.1.3. Impact of hydrogen induction with Volumetric efficiency

The amount of air that is sucked by the engine while it is performing the suction action is what determines the volumetric efficiency, also known as VE. A number of factors, including the temperature of the air intake, the expansion of residual gas in the clearing volume, and the loading conditions of the engine, should be considered.

4.1.3.1. Impact of hydrogen addition on volumetric efficiency on oil mill waste oil. VE is used to access the breathing ability of the engine, which is reliant on the air temperature intake, residual gas temperature and inlet pressure of the engine. The [Fig. 6](#) expresses the details of VE deviation concerned with oil mill waste oil and hydrogen. As the load increases, VE drops owing to the rise in operating temperature. The VE was obtained at full load condition for Diesel, OM100, OM100H5, OM100H10 is 80.49%, 77.92%, 77.74% and 77.73%. According to the data, the VE for OM100H10 fell by about 3.54% when compared to Diesel OM100. In all operating conditions, Diesel OM100 has a greater volumetric efficiency than both OM100H5 and OM100H10. As a result of the presence of hydrogen in the sucking and compressing processes, hydrogen is accumulated in the crevice volumes. This hydrogen is subsequently released back into the combustion chamber during the latter phases of the combustion process. A higher diffusivity and a wide range of flammability make it possible for hydrogen to be oxidized, which in turn raises the temperature of the combustion process. Remaining gas in the clearing volume increased as a result, which resulted in the formation of a barrier that prevented new air from entering the subsequent or subsequent cycle.

4.1.3.2. Impact of hydrogen on volumetric efficiency on oil mill waste oil-camphor oil blend. The [Fig. 7](#) described the details of VE deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. The VE was obtained at full load condition for Diesel, OM100, OC50, OC50H5, OC50H10 is 80.49%, 79.32%, 79.09%, and 79%. In comparison to Diesel, the [Fig. 7](#) that was obtained indicates that the VE for OC50H10 is about 1.88% lower, while it is approximately 1.60% higher than that of OM100H10. When camphor oil, which has a lower cetane rating, is combined with waste oil from oil mills, the mixture goes through a longer ignition delay and more expansion processes, which finally leads to a quenching effect. As a consequence of this, it is essential to reduce the temperature of the exhaust gas. A decrease in volumetric efficiency is brought about by the substitution of hydrogen molecules for air molecules. In addition, the higher reactivity and diffusivity of hydrogen contribute to the promotion of combustion in later stages, which ultimately results in a reduction in VE. [Manickam et al. \(2025\)](#) observed a decline in volumetric efficiency with an increasing hydrogen induction rate due to the displacement of air molecules by hydrogen, a finding consistent with the present findings.

4.1.4. Exhaust gas temperature

EGT shows how much heat energy leaves the engine or dissipates into the sink. Therefore, it is essential to get the low value as much as possible.

4.1.4.1. Impact of hydrogen on exhaust gas temperature using oil mill waste oil. The [Fig. 8](#) disclosed the details of EGT deviation concerned with oil mill waste oil and hydrogen. The EGT was obtained at full load condition for Diesel, OM100, OM100H5, OM100H10 is 634.27 K, 644.24 K, 655.15 K, 656.38 K. As a result of the value, the EGT for OM100H10 is reduced by about 3.36 % in comparison to Diesel. On the other hand, when it comes to the formation of the air-fuel combination, the high viscosity and low volatility of OM100 are both aspects that contribute to the poor formation. The reason for this is because the spray formation is not very good, which leads to a larger core area and a smaller envelope. The course of the combustion process is slowed down and the length of the process is extended as a result of this. Offering hydrogen in combination with OM100 results in a rise in the exhaust gas temperature (EGT), which is a consequence of a strong flammability range, which helps to support the afterburning combustion and provides more heat to the exhaust.

4.1.4.2. Impact of hydrogen induction on exhaust gas temperature using oil mill waste oil – camphor oil blend. The [Fig. 9](#) expounds the details of EGT deviation concerned with oil mill waste oil-camphor oil blend and

Table 8
Equations and Model Details for Oil Mill Waste Oil-Camphor Oil Blend.

Parameter	Model equation	Model type	P- value
ExEL	$\text{ExEL} = 0.000960 + 7.09928\text{E} - 06 * \text{LD} - 0.000016 * \text{HG} - 2.22955\text{E} - 07 * \text{LD} * \text{HG} + 6.14244\text{E} - 08 * \text{LD}^2 + 1.24336\text{E} - 06 * \text{HG}^2$	Quadratic	< 0.0001
EnEL	$\text{EnEL} = 0.092755 + 0.001665 * \text{LD} - 0.000468 * \text{HG} - 0.000042 * \text{LD} * \text{HG} + 0.000028 * \text{LD}^2 + 0.000017 * \text{HG}^2$	Quadratic	< 0.0001
TEL	$\text{TEL} = 0.000544 + 1.10379\text{E} - 07 * \text{LD} - 0.000021 * \text{HG} - 1.68930\text{E} - 07 * \text{LD} * \text{HG} + 3.92632\text{E} - 08 * \text{LD}^2 + 1.37643\text{E} - 06 * \text{HG}^2$	Quadratic	< 0.0001
FE	$\text{FE} = 5.26017 + 0.084983 * \text{LD} - 0.076170 * \text{HG} - 0.001006 * \text{LD} * \text{HG} + 0.000432 * \text{LD}^2 + 0.005624 * \text{HG}^2$	Quadratic	< 0.0001
ExE	$\text{ExE} = 16.65113 + 0.359077 * \text{LD} + 0.340701 * \text{HG} + 0.001354 * \text{LD} * \text{HG} - 0.001579 * \text{LD}^2 - 0.016992 * \text{HG}^2$	Quadratic	< 0.0001
Aeg	$\text{Aeg} = 4.73652 - 0.004359 * \text{LD} + 0.041152 * \text{HG} + 0.000780 * \text{LD} * \text{HG} + 0.000244 * \text{LD}^2 - 0.004595 * \text{HG}^2$	Quadratic	0.0003
EG	$\text{EG} = 0.016000 + 0.000118 * \text{LD} - 0.000260 * \text{HG} - 3.71591\text{E} - 06 * \text{LD} * \text{HG} + 1.02374\text{E} - 06 * \text{LD}^2 + 0.000021 * \text{HG}^2$	Quadratic	< 0.0001
Ad	$\text{Ad} = 4.80002 + 0.035496 * \text{LD} - 0.077957 * \text{HG} - 0.001115 * \text{LD} * \text{HG} + 0.000307 * \text{LD}^2 + 0.006217 * \text{HG}^2$	Quadratic	< 0.0001
SI	$\text{SI} = 1.14170 + 0.007601 * \text{LD} + 0.006099 * \text{HG} + 0.000058 * \text{LD} * \text{HG} - 0.000032 * \text{LD}^2 - 0.000385 * \text{HG}^2$	Quadratic	< 0.0001
Acw	$\text{Acw} = 0.686621 + 0.006232 * \text{LD} + 0.024594 * \text{HG}$	Linear	< 0.0001
BSHC	$\text{BSHC} = 0.766099 - 0.013395 * \text{LD} + 0.008210 * \text{HG} - 0.000103 * \text{LD} * \text{HG} + 0.000089 * \text{LD}^2 - 0.000505 * \text{HG}^2$	Quadratic	0.0125
Smoke opacity	$\text{Smoke opacity} = 19.46667 + 0.605333 * \text{LD} - 0.393333 * \text{HG}$	Linear	< 0.0001
BSNO	$\text{BSNO} = 10.24816 + 0.040492 * \text{LD} + 0.028205 * \text{HG} + 0.000227 * \text{LD} * \text{HG} - 0.000463 * \text{LD}^2 + 0.000429 * \text{HG}^2$	Quadratic	< 0.0001
BSCO ₂	$\text{BSCO}_2 = 972.52115 - 4.62873 * \text{LD} - 9.29337 * \text{HG} + 0.012088 * \text{LD} * \text{HG} + 0.041727 * \text{LD}^2 + 0.047933 * \text{HG}^2$	Quadratic	< 0.0001
BSCO	$\text{BSCO} = 33.01988 - 0.826405 * \text{LD} + 0.145402 * \text{HG} - 0.007041 * \text{LD} * \text{HG} + 0.006973 * \text{LD}^2 + 0.005071 * \text{HG}^2$	Quadratic	0.0116
EGT	$\text{EGT} = 445.26778 + 0.145000 * \text{LD} + 0.213667 * \text{HG} + 0.014480 * \text{LD} * \text{HG} + 0.017357 * \text{LD}^2 - 0.076467 * \text{HG}^2$	Quadratic	< 0.0001
BTE	$\text{BTE} = 12.38447 + 0.379397 * \text{LD} + 0.116530 * \text{HG} + 0.000468 * \text{LD} * \text{HG} - 0.001929 * \text{LD}^2 - 8.23411\text{E} - 10 * \text{HG}^2$	Quadratic	< 0.0001
VE	$\text{VE} = 90.68582 - 0.114389 * \text{LD} - 0.334695 * \text{HG} + 0.003120 * \text{LD} * \text{HG}$	2FI	< 0.0001
BSEC	$\text{BSEC} = 19.94958 - 0.172064 * \text{LD} - 0.078857 * \text{HG} + 0.000194 * \text{LD} * \text{HG} + 0.000885 * \text{LD}^2 + 0.000310 * \text{HG}^2$	Quadratic	< 0.0001

hydrogen. At full load conditions, the EGT values for Diesel, OM100, OC50, OC50H5, and OC50H10 were determined to be 634.27 K, 632 K, 641.14 K, 656.38 K, and 642.25 K, respectively. According to the Fig. 9 that was obtained, the EGT for OC50H10 is about 1.24 % higher than that of Diesel, while it is approximately 2.2 % lower than that of OM100H10. While the OM100 generates exhaust gas at a substantially higher temperature, the OMC50 generates exhaust gas at a significantly lower temperature due to its higher expansion ratio. When the hydrogen is supplied using OMC50, the EGT is lower than when it is delivered with OC50H5 and OC50H10 of the same kind. In the final phases of combustion, when the fuel is consumed close to the cylinder wall, the temperature of the exhaust gas is raised. This is because the fuel is being

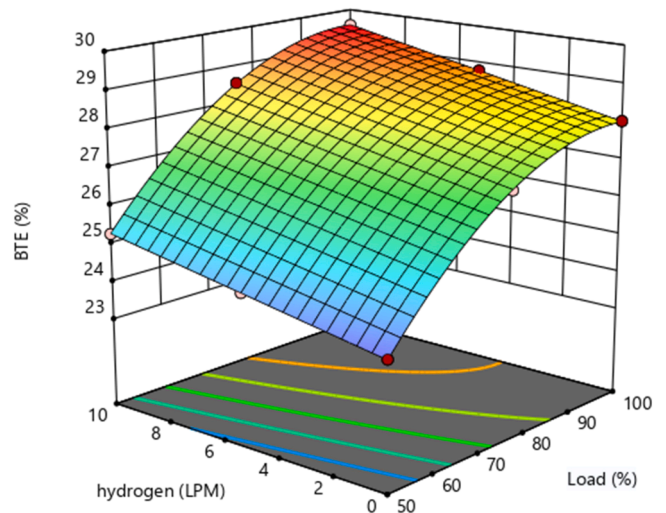


Fig. 2. Influence of hydrogen participation and load on BTE for oil mill waste oil.

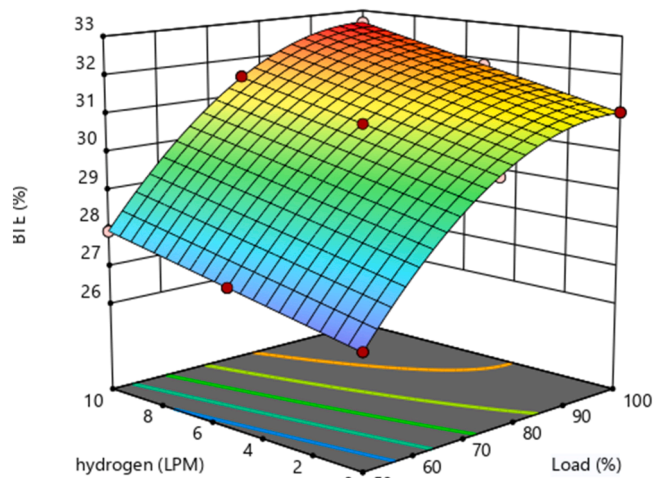


Fig. 3. Impact of hydrogen participation and load on BTE for oil mill waste oil-camphor oil blend.

burned down. An excellent flammability range and a higher reaction rate are the means by which this objective may be realized. When mixing hydrogen with *Chlorella vulgaris* algae oil, Subburayalu Ramesh and Thiagarajan (2024b) witnessed an upward trend in EGT similar to our findings, which they attributed to the heightened heating value of hydrogen.

4.2. Emissions characteristics

With the exception of smoke opacity, emissions parameters are presented in terms of brake specific emissions. It is vital to understand the emissions generated by different power generation under various operating situations.

4.2.1. Brake specific carbon monoxide

BSCO emissions depend upon the air-fuel ratio, loading conditions of the engine, and viscosity and carbon content of the fuel.

4.2.1.1. Impact of hydrogen on Brake specific carbon monoxide emissions using oil mill waste oil. The Fig. 10 elucidates the details of BSCO deviation concerned with oil mill waste oil and hydrogen. In the case of

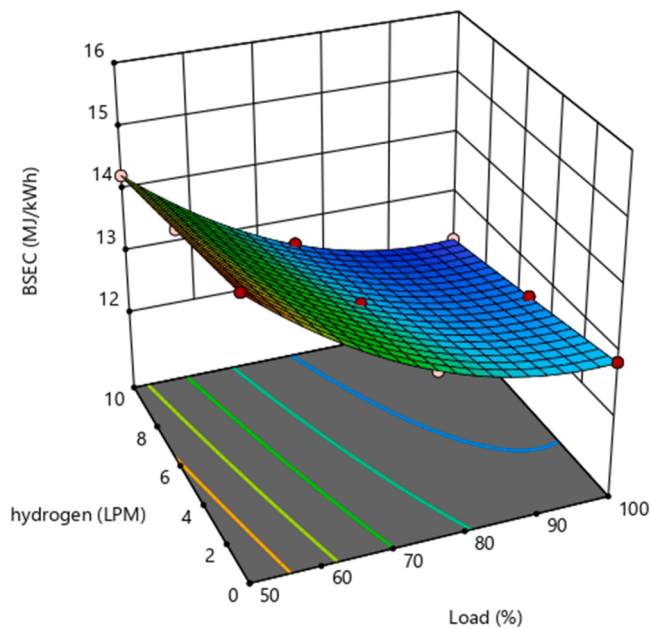


Fig. 4. Interaction of hydrogen induction and load on BSEC for oil mill waste oil.

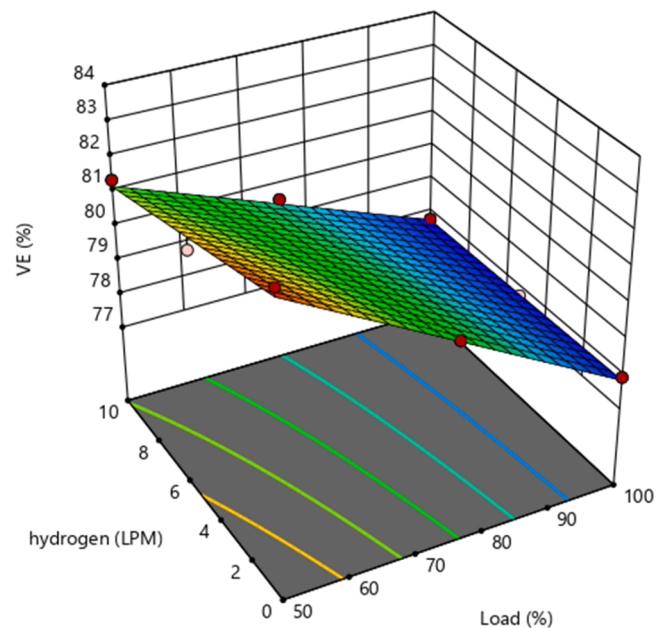


Fig. 6. Details of the impact of hydrogen introduction and load on volumetric efficiency for oil mill waste oil.

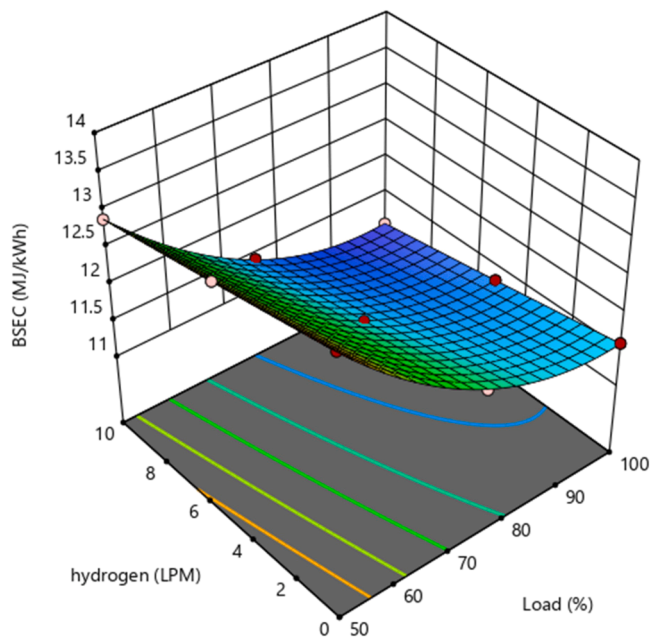


Fig. 5. Impact of hydrogen induction and load interaction on BSEC for oil mill waste oil-camphor oil blend.

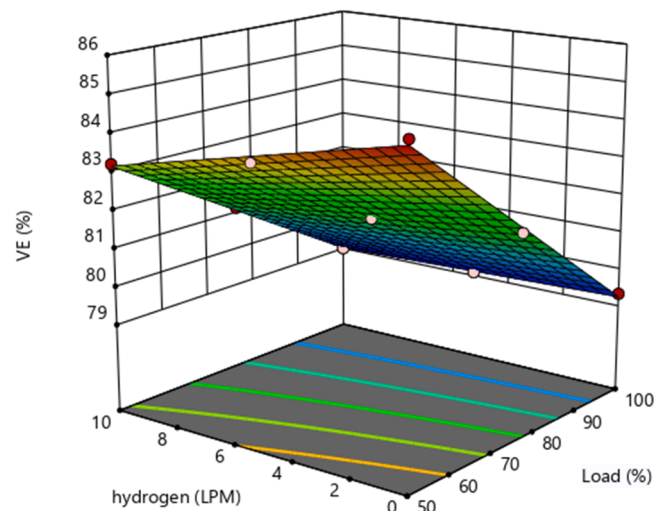


Fig. 7. Influence of hydrogen participation and load on VE for oil mill waste oil-camphor oil blend.

Diesel, OM100, OM100H5, and OM100H10, the carbon monoxide emission was measured under full load conditions and found to be 11.53 g/kWh, 26.19 g/kWh, 24.16 g/kWh, and 22.20 g/kWh respectively. When compared to diesel, the carbon monoxide emission from OM100H10 is about 48.05 % more than that of diesel vehicle. The following factors contributed to the poor development of the air-fuel combination despite the high viscosity of OM100 during the experiment: OM100 is responsible for the formation of larger fuel droplets, which results in an increase in the core area of the fuel droplets and a decrease in the envelope area. This, in turn, reduces the amount of air and fuel droplets that are mixed together. 2) A substance with a larger molecular weight has a higher boiling point, which causes it to take

longer to reach the saturation stage and has a poor evaporation process because of its low volatility. The OM100 suffers from incomplete combustion as a result of the reason that was described above, which results in greater BSCO emissions regardless of the loading circumstances encountered. Because of the following factors, the participation of hydrogen in conjunction with OM100 results in a reduction in BSCO emissions: The instant combustion properties of hydrogen are characterized by quick burning, which contributes to an increase in the peak pressure inside the cylinder. In consequence of this, it accelerates the rate of oxidation as well as the rate of heat transfer, which immediately results in a reduction of the BSCO emissions. 2) The participation of hydrogen results in a decrease in the quantity of hydrocarbon fuel, which in turn results in an instantaneous reduction in the number of carbon atoms that are involved in the combustion processes. After conducting experiments in heavy-duty and light-duty engines, Talibi et al. (2018), observed the reduction in CO emissions in line with current research results due to better oxidation caused by the higher

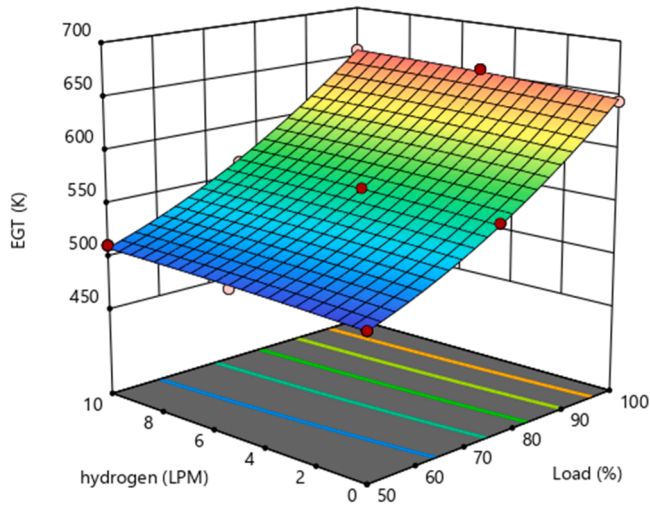


Fig. 8. Influence of hydrogen participation and load on EGT for oil mill waste oil.

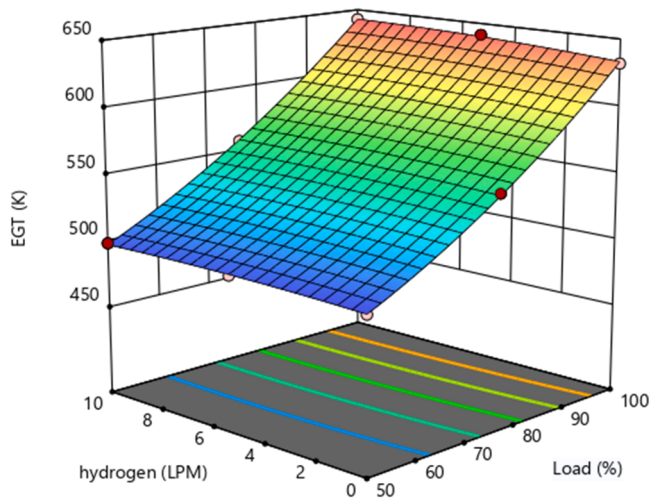


Fig. 9. Influence of hydrogen participation and load on EGT for oil mill waste oil - camphor oil blend.

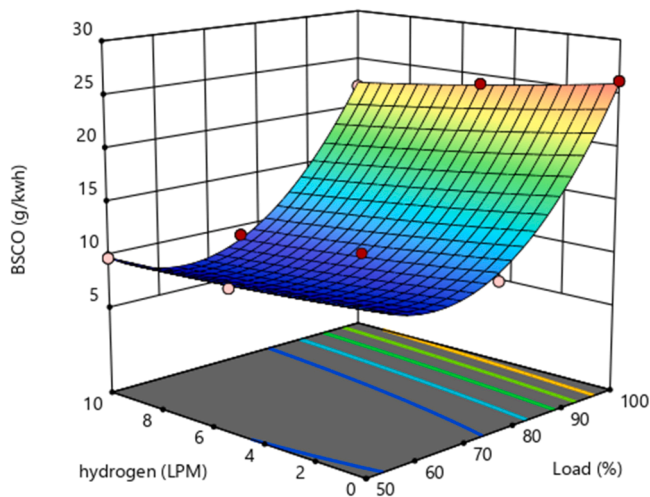


Fig. 10. Influence of hydrogen participation and load on BSCO for oil mill waste oil.

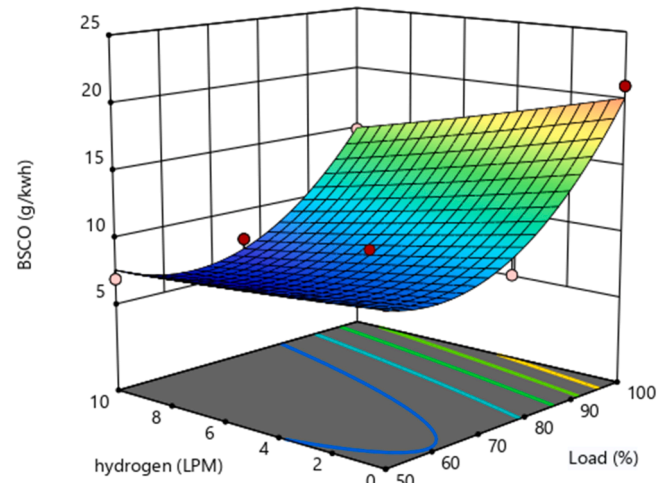


Fig. 11. Influence of hydrogen participation and load on BSCO for oil mill waste oil - camphor oil blend.

temperature combustions.

4.2.1.2. Impact of hydrogen induction on Brake specific carbon monoxide emissions using oil mill waste oil – camphor oil blend. The Fig. 11 reveals the details of BSCO deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. Diesel, OM100, OC50, OC50H5, and OC50H10 were tested under full load conditions, and the results showed that the carbon monoxide emission was 11.53 g/kWh, 21 g/kWh, 16.64 g/kWh, and 14.93 g/kWh respectively. The BSCO for OC50H10 has grown by about 22.78% in comparison to Diesel, while it has dropped by approximately 75% in comparison to OM100 and by approximately 48% in comparison to OM100H10. The following are some of the reasons why the inclusion of camphor oil mixed with waste oil from oil mills results in a reduction in BSCO emissions: i) The low viscosity of camphor oil helps to reduce the size of the droplets, which in turn facilitates quicker evaporation and higher air-fuel mixing. ii) The low cetane number of camphor oil makes the fuel oxidation processes more efficient. This is because the increased in-cylinder peak pressure and temperature facilitates greater heat transmission, which in turn enhances the fuel oxidation processes. As a consequence of the longer ignition delay, the in-cylinder peak pressure and temperature will increase. This is because the longer ignition delay will cause more fuel to be burned in the early phases of combustion. The following are some of the reasons why the engagement of hydrogen with OMC50 contributes to the lowering of BSCO. The use of carbon-free hydrogen in combustion results in a reduction in the quantity of carbon-based fuel that is consumed. ii) The instant combustion properties of hydrogen speed up the combustion process and encourage the successful oxidation of carbon atoms that are present in the combustion processes. As a result of the favourable behaviour of hydrogen, the OMC50 burning processes are supported, which in turn results in a reduction in BSCO emissions.

According to Nurullah et al. (2024), the lack of carbon atoms in hydrogen fuel reduces CO emissions, which is consistent with existing findings.

4.2.2. Brake specific hydrocarbon emissions

BSHC emissions are unreacted fuel coming out of the tailpipe during the cyclic process. BSHC is not only emissions but also conveys the fuel loss during the energy conversion processes.

4.2.2.1. Impact of hydrogen on Brake specific hydrocarbon emissions using oil mill waste oil. The Fig. 12 expounds the details of BSHC deviation concerned with oil mill waste oil and hydrogen. Hydrocarbon emissions were measured under full load conditions for Diesel, OM100, OM100H5,

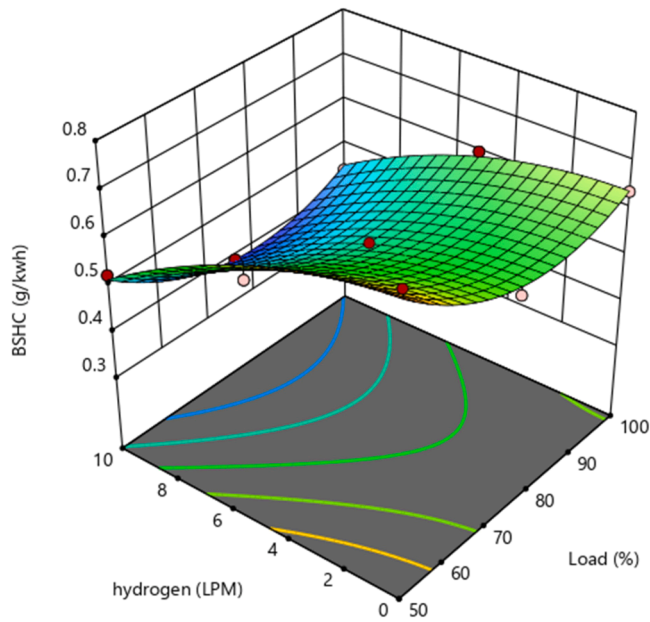


Fig. 12. Influence of hydrogen participation and load on BSHC for oil mill waste oil.

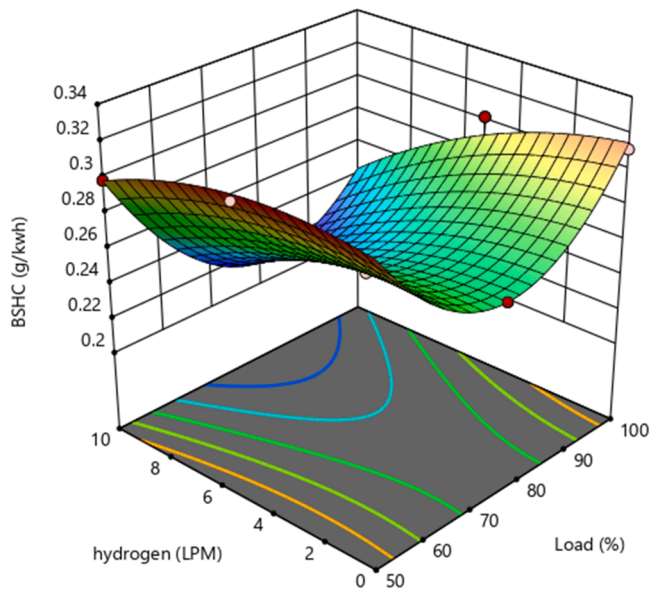


Fig. 13. Influence of hydrogen participation and load on BSHC for oil mill waste oil - camphor oil blend.

and OM100H10, and they were found to be 0.23 g/kWh, 0.63 g/kWh, 0.60 g/kWh, and 0.44 g/kWh, respectively. According to the value, the hydro-carbon emission for OM100H10 is about 47.48% more than that of Diesel in comparison). The BSHC that is produced by OM100 is higher for the reasons that are listed below. i) Incomplete combustion, which is brought on by larger droplets, inadequate vaporization, fuel mixing that occurs under air conditions, sac volume, and decreased oxidation processes. Jaikumar et al. (2019) manifested a rise in hydrogen concentrations, dropping HC emissions. Most particularly, drop in HC emissions from 113 ppm to 34 ppm while using the B20 (Guizotia abyssinica Methyl Ester–Diesel Blend) in a 3.5 kW CI engine and HC outcomes similar to our current research outcome.

4.2.2.2. Impact of hydrogen induction on Brake specific hydrocarbon emissions using oil mill waste oil – camphor oil blend. The Fig. 13 narrates the details of BSHC deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. Diesel, OM100, OC50, OC50H5, and OC50H10 were tested under full load conditions, and the results showed that the hydrocarbon emission was 0.23 g/kWh, 0.31 g/kWh, 0.30 g/kWh, and 0.23 g/kWh respectively. Based on the value that was obtained, the hydrocarbon emission for OC50H10 results in a little rise of about 1.88 % in comparison to Diesel, while it decreases by approximately 90 % in comparison to OM100 and by approximately 70 % in comparison to OM100H10. Due to the slower combustion produced by the poor atomization of greater viscosity but lower than OM100, OMC50 is responsible for the generation of larger levels of hydrocarbon emissions. Due to the improvised combustion processes generated by the improvised atomization greater envelope-to-core area), OMC50 exhibits reduced BSHC emissions in comparison to OM100. This is because OMC50 is free from the under-mixing of air and fuel. A decreased cetane grade of camphor oil causes an increase in the crucial temperature and pressure, which in turn speeds up the pace of oxidation since it allows for more efficient heat transmission. As a consequence of this, the BSHC emissions are reduced. On the other hand, an increase in peak pressure might potentially give rise to an expansion cooling process, which would result in an increase in BSHC emissions as a consequence of the quenching effect. The decrease of viscosity and the burning of a greater quantity of fuel at the beginning of the combustion process, on the other hand, assists in the oxidation of fuel and reduces the emissions of BSHC. The presence of hydrogen in air intake systems causes a change in the ratio of air to fuel, which results in the anticipation of an increase in the amount of BSHC emissions occurring. In this particular instance, the presence of hydrogen in air intake systems reduces the amount of BSHC emissions. Heat transfer is improved and oxidation processes are boosted as in-cylinder peak pressure and temperatures increase. This is because instant rapid characteristics and a higher heating value of hydrogen contribute to these improvements. It does this by decreasing the amount of hydrocarbon fuel used in the main injector, which in turn decreases the amount of BSHC emissions. Annamalai and Murugesan (2024) establish that adding hydrogen to oxygenated biofuels encourages combustion, which produces lower levels of HC emissions similar to our findings.

4.2.3. Brake specific carbon dioxide emissions

BSCO₂ indicates or measures the successful oxidation of the carbon

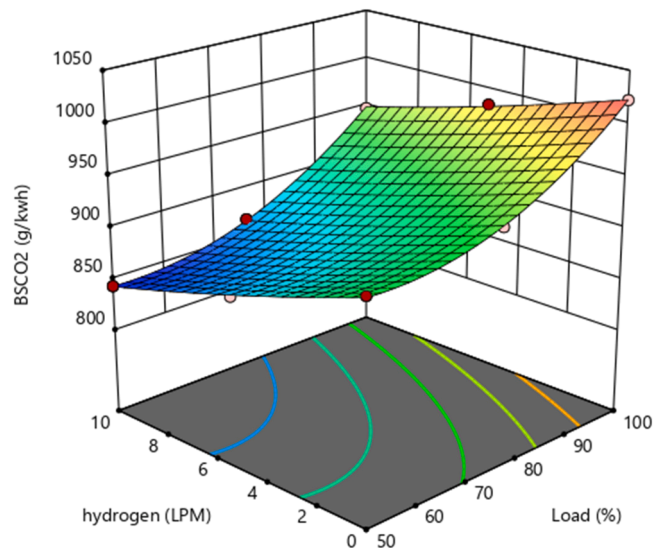


Fig. 14. Effect of hydrogen participation and load on BSCO₂ for oil mill waste oil.

atoms. From the combustion perspective, carbon dioxide emissions are unavoidable. The BSCO₂ emissions show the positive participation of hydrocarbon fuel in the combustion or energy conversion processes.

4.2.3.1. Impact of hydrogen on Brake specific carbon dioxide emissions using oil mill waste oil. The Fig. 14 presents the details of BSCO₂ deviation concerned with oil mill waste oil and hydrogen. It has been noticed that the BSCO₂ of the OM100 is 1022.442 g/kWh while it is operating at full load. This value is 22.70%, 3.82%, and 7.88% higher than diesel, OM100S, and OM100H10 respectively. When there are more OM100 molecules, there are more carbon atoms that are able to take part in the combustion processes. This is because the number of carbon molecules has grown. Because hydrogen has a higher heating value than other fuels, it minimizes the quantity of fuel that is required in the main injector. Hydrogen is a fuel that does not emit any carbon dioxide from its combustion. When compared to OM100, OM100H5 and OM100H10 have higher in-cylinder peak pressure, and they also take part in the process of oxidizing carbon atoms. OM100H5 and OM100H10 are also participating in the process. On the other hand, the active involvement of hydrogen results in a nearly complete reduction of the emissions of BSCO₂. Rajak et al. (2020) confirmed the drop in BSCO₂ emissions like our results while adding the h₂ with different biofuels as a result of a lower carbon-to-hydrogen ratio.

4.2.3.2. Impact of hydrogen gas induction on Brake specific carbon dioxide using oil mill waste oil – camphor oil blend. The Fig. 15 explains the details of BSCO₂ deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. At full load, OC50, OC50H5, and OC50H10 had cut down BSCO₂ emissions than OM100 by 10.22%, 15.15%, and 20.29%, respectively. When compared to OM100, OC50 has a lower total amount of carbon atoms. In spite of the fact that OC50 has favourable combustion characteristics, the OM100 produces more than BSCO₂ when compared to OC50. Supplying hydrogen with OC50 results in a decrease in the BSCO₂ owing to a decrease in the quantity of carbon atoms that are involved in the combustion processes and an increase in the number of hydrogen atoms that are effectively involved in the combustion processes.

4.2.4. Brake specific nitrogen monoxide

Brake specific nitrogen monoxide (BSNO) are toxic invisible emissions coming out of the exhaust pipe as a result of the combustion of hydrocarbons. Usually, BSNO emissions are due to the temperature

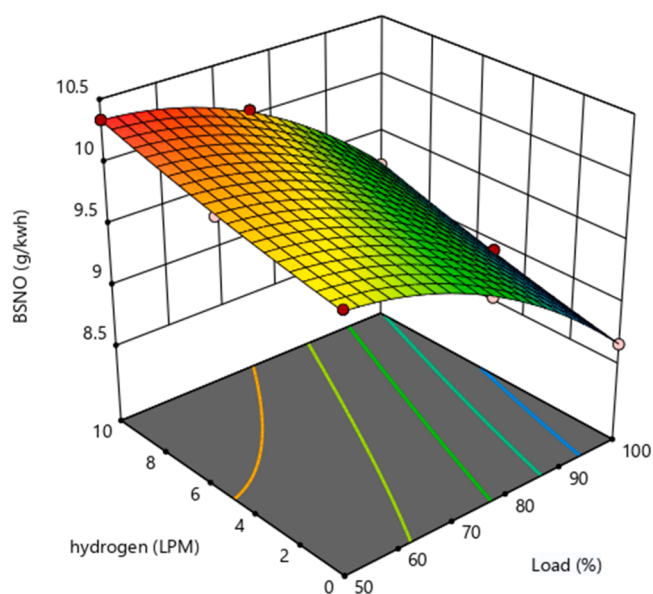


Fig. 16. Influence of hydrogen participation and load on BSCO₂ for oil mill waste oil.

prompt NO emissions.

4.2.4.1. Impact of hydrogen on Brake specific nitrogen monoxide using oil mill waste oil. The Fig. 16 depicts the details of BSNO deviation concerned with oil mill waste oil and hydrogen. The generation rate of thermal NO is contingent upon temperature and provides an extra combustion product. In general, higher temperatures increase the likelihood of more nitrogen oxide generation, and excess oxygen is seen in the later stages of combustion and its length. Turbulence is another aspect that promotes greater mixing of fresh charge with air and creates conditions conducive to larger NO emissions. The BSNO of diesel is 8.46 g/kWh while operating at rated load, which is 2.15%, 5.19%, and 8.08% lower than the BSNO of OM100, OM100H5, and OM100H10, respectively. OM100 has slower combustions, although this is owing to a lower stoichiometric air fuel ratio, which results in greater BSNO emissions. OM100H5 and OMH10 exhibit increased BSNO levels due to

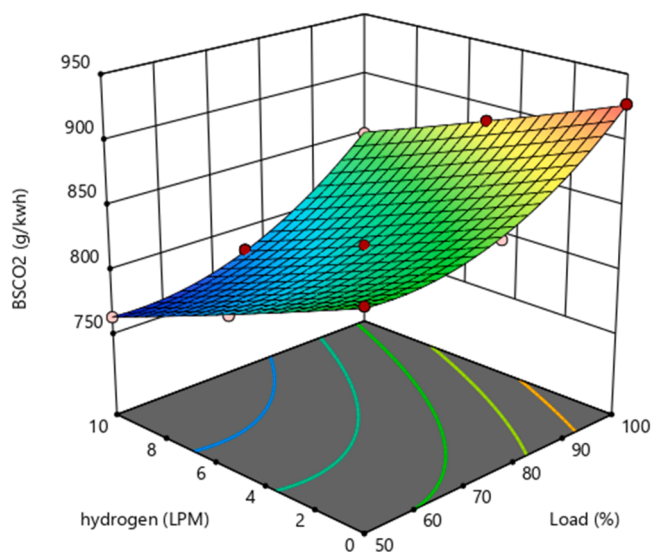


Fig. 15. Influence of hydrogen participation and load on BSCO₂ for oil mill waste oil-camphor oil blend.

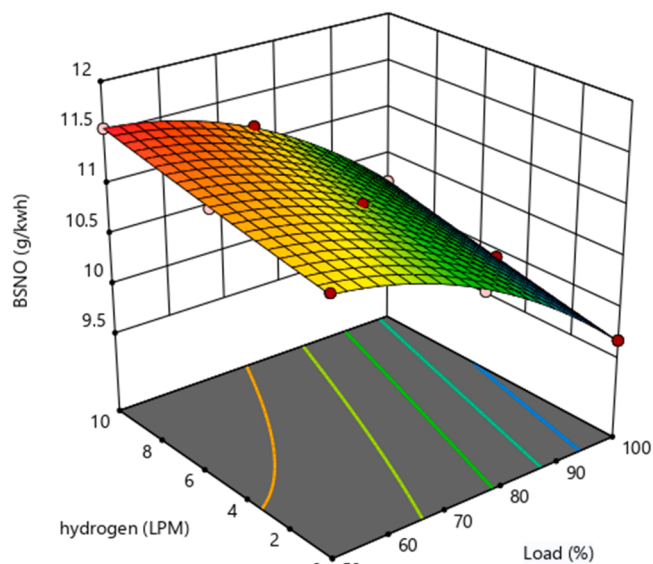


Fig. 17. reveals the details of BSNO deviation concerned with oil mill waste oil-camphor oil blend and hydrogen.

greater flame temperatures, faster premixed combustion, and higher flame temperatures even after combustion. Ramalingam et al. (2022) noted the rise in NO_x emissions due to dominant post-flame charge NO_x emissions, like our results.

4.2.4.2. Impact of hydrogen induction on Brake specific nitrogen monoxide emissions using oil mill waste oil – camphor oil blend. Fig. 17 shows that when the concentration of camphor oil in the studied biofuels increases, so does the NO level. At rated operating circumstances, OC50, OC50H5, and OC59H10 emit 12.41%, 14.70%, and 16.99% more BSNO than diesel, respectively. This is related to the formation of increased turbulence due to fuel accumulation and a sudden increase in burning rate during pre-mixed combustion induced by a longer ignition delay due to the camphor oil's lower cetane rating. Because waste mill oil is more viscous than camphor oil, it burns slower due to the larger size and poor breakdown of the fuel droplets, lowering combustion temperatures and reducing NO emissions. As a result, raising the concentration of hydrogen and camphor on oil mill waste oil overcomes the effect of higher viscosity and leads to increase NO emissions. Because of the greater heat release rate brought on by the hydrogen induction using Camelina sativa oil, the BSNO findings of Pawlak et al. (2025). are comparable to the results that have been given.

4.2.5. Smoke opacity

Smoke opacity convey the amount of visible emissions leaving out of the tailpipe during the cyclic processes in the interest of thermal cracking of carbon atoms.

4.2.5.1. Impact of hydrogen on smoke emissions using oil mill waste oil. The Fig. 18 disclosed the details of smoke opacity deviation concerned with oil mill waste oil and hydrogen. In comparison to diesel fuel, OM100 has a smoke opacity that is 29.01% higher, coming in at 88.90% when it is operating at its rated power. When compared to the OM100, the smoke opacity of the OM100H5 and OM100H10 is lowered by 5.58 and 10.84 %, respectively. A slower oxidation rate is experienced by OM100, which is a high-carbon fuel. This results in more carbon atoms being produced in the latter phases of combustion. This suffocates the additional carbon atoms that are not present in the oxygen content, which causes the smoke to have a higher opacity. A slower oxidation rate is experienced by OM100, which is a high-carbon fuel. This results in more carbon atoms being present in the latter phases of combustion, which undergoes thermal cracking. This suffocates the thermally cracked carbon atoms that are not present in the oxygen content, which causes higher smoke opacity.

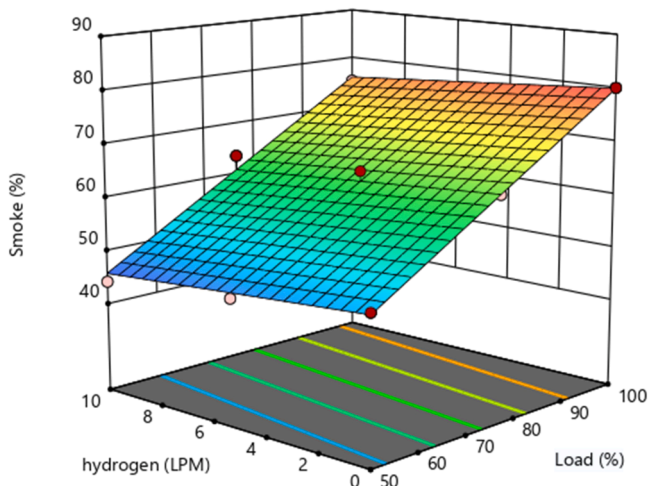


Fig. 18. Influence of hydrogen participation and load on smoke for oil mill waste oil.

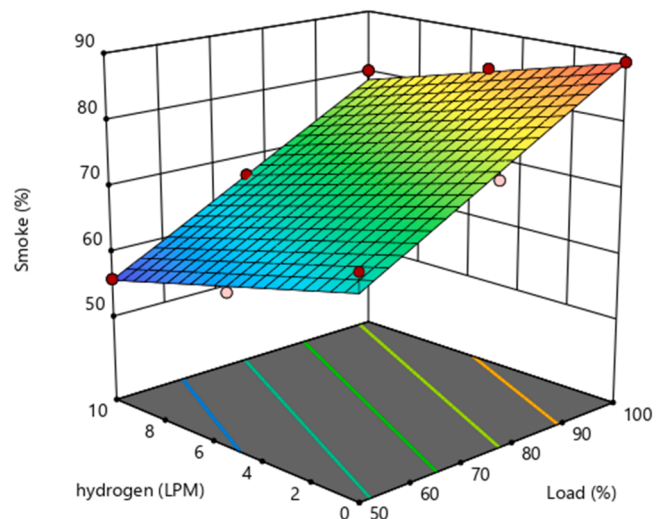


Fig. 19. Influence of hydrogen participation and load on smoke for oil mill waste oil-camphor oil blend.

4.2.5.2. Impact of hydrogen induction on smoke opacity emissions using oil mill waste oil – camphor oil blend. The Fig. 19 manifests the details of smoke opacity deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. Compared to OM100, OC50 produces 10.84% less smoke opacity at rated working conditions. Compared to OC50H5 and OC50H10, OC50 has 4.84% and 6.47% more smoke opacity. Camphor oil, a lower carbon fuel, contributes to decreased smoke opacity due to the decrease in the quantity of carbon atoms engaged in the latter stages of combustion. Providing hydrogen creates a greater degree of homogeneity with molecules of air and assists in the later stages of combustion by increasing heat transfer rate, which reduces smoke opacity. According to Arumugam et al. (2024), higher diffusivity and a broad range of hydrogen flammability assist the oxidation of soot particles at the latter stages of combustion, which results in lesser smoke generation. These findings are consistent with the smoke data that were reported.

4.3. Exergy characteristics

4.3.1. Fuel exergy

Fuel exergy (FE) indicates the maximum potential fuel energy availability in terms of a theoretical perspective which revolves around fuel compositions, volume flow rate and energy density of the fuel.

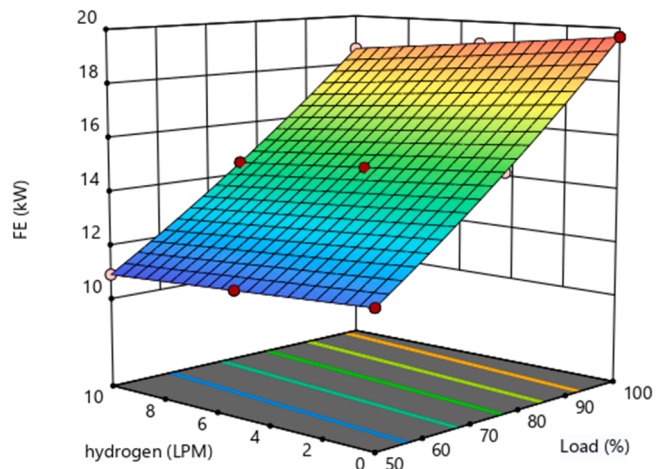


Fig. 20. Influence of hydrogen participation and load on FE for oil mill waste oil.

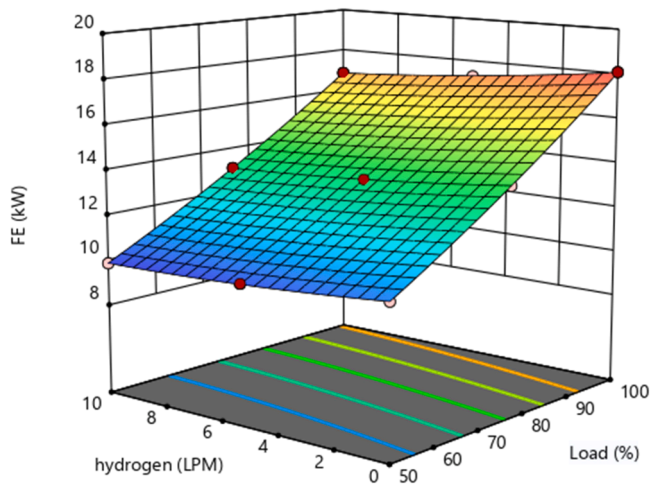


Fig. 21. Influence of hydrogen participation and load on FE for oil mill waste oil-camphor oil blend.

4.3.1.1. Impact of hydrogen on Fuel exergy using oil mill waste oil. The Fig. 20 expresses the details of FE deviation concerned with oil mill waste oil and hydrogen. In comparison to the diesel, OM100H5, and OM100H10, the OM100's FE under full load circumstances is 19.67 kW, which is 10.46%, 2.73%, and 5.47% higher. OM100 has the higher FE owing to the increased mass flow rate of the fuel to produce the same power due to the combined impact of higher density and lower heating value of the fuel, even though it contains higher specific exergy. Inclusion of hydrogen is expected to raise the FE due to a reduction in specific exergy caused by the absence of carbon atoms in the fuel. But due to the higher heating value, the highly reactive nature and the high degree of homogeneity curtail the FE.

4.3.1.2. Impact of hydrogen induction on Fuel exergy using oil mill waste oil – camphor oil blend. The Fig. 21 depicts the details of FE deviation concerned with an oil mill waste oil-camphor oil blend and hydrogen. Compared to OM100, OMC50 has the lower FE. At full load, the OMC50's fuel exergy of 18.09 kW is 5.2% and 14.18% lower than diesel and OM100, respectively, but 4.53% and 7.17% higher than OMC50H50 and OMC50H10. Due to lower carbon and hydrogen molecules along with oxygen, it is expected to have a lesser value of FE for OMC50. But lower viscosity and cetane number support the heat release at the right time in the combustion and trim down the FE. The incorporation of

hydrogen with OMC50 in combustion lowers the FE because it generates more heat due to improved mixing, a wider spectrum of combustibility, quicker flame speed, bigger flame temperature, and a higher heating value of hydrogen.

4.3.2. Engine cooling water exergy

A_{cw} conveys how much exergy is lost to the environment through the engine cooling water, which is a matter of engine cooling water flow rate, temperature gradient and boundary conditions of the cylinder wall.

4.3.2.1. Impact of hydrogen on Exergy rate of engine cooling water using oil mill waste oil. Fig. 22 Highlighted the specifics of A_{cw} deviation related to oil mill waste oil and hydrogen. It has been determined that the rated power of the OM100 is 0.849 kW, which is a decrease of 26.98%, 16.42%, and 30.71% in comparison to diesel, OM100H5, and OM100H10 that are accordingly lower. A_{cw} of the OM100 has a reduced rate of oxidation in the presence of high viscosity. As a result, it produces lower in-cylinder temperatures and pressures, which do not support the heat transfer rate from combustion gas to wall and wall to engine cooling water. Topping up the hydrogen with OM100 increases the A_{CW} in favour of a larger convection zone generated by greater in-cylinder peak pressure and temperature, which increases the total heat transfer coefficient owing to the presence of turbulence caused by the rapid rate of pressure rise.

4.3.2.2. Impact of hydrogen induction on Exergy rate of engine cooling water using oil mill waste oil – camphor oil blend. The Fig. 23 depicts the details of A_{cw} deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. A_{cw} is determined to be 1.30 kW for OMC50 when it is operating at its rated power, which is 12.06% and 53.46% greater than diesel and OM100 respectively, but 9.95% and 15.40% lower than OMC50H5 and OMC50H10 respectively. The low viscosity and low cetane of OMC50 produce a higher A_{cw} due to enhanced heat transfer characteristics or excellent heat transfer boundaries, which are developed as a result of high peak pressure and temperature, especially at premixed combustion. This allows for sufficient or additional time for heat exchanges to occur between the combustion products and the cylinder wall while the engine is operating in convection mode, as well as between the cylinder wall and the water that is cycled in the engine jacket's cooling water. Therefore, A_{cw} for OMC50 is higher than OM100. The involvement of hydrogen gas with OMC50 hikes the in-cylinder peak pressure and temperature as a result, improving the heat transfer coefficient between hot gas and the cylinder wall. Therefore, more heat is transferred to engine cooling water. Higher uniformity of hydrogen

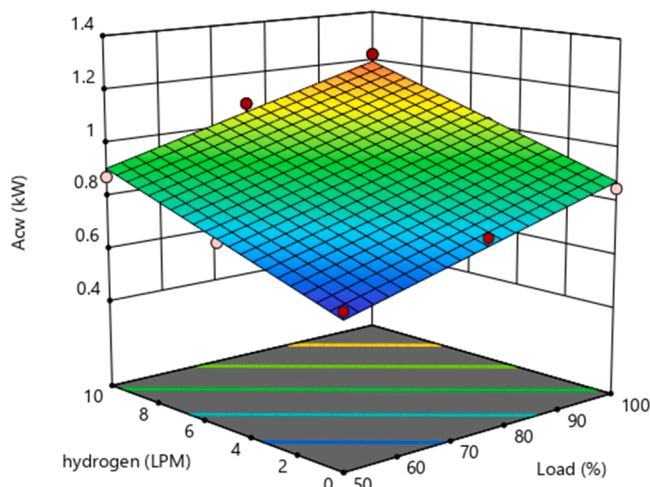


Fig. 22. Influence of hydrogen participation and load on A_{cw} for oil mill waste oil.

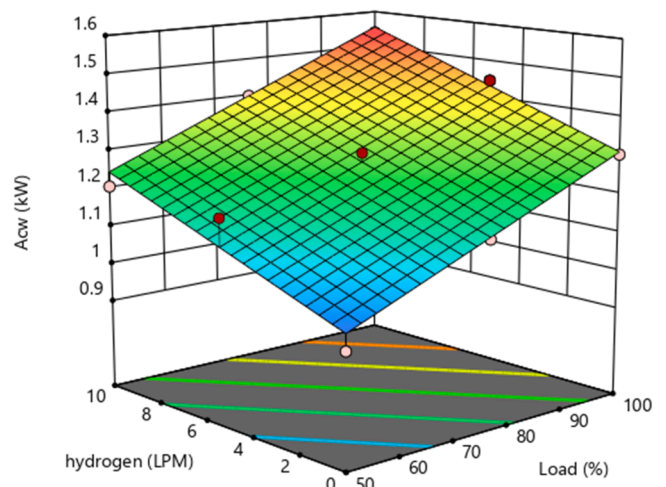


Fig. 23. Influence of hydrogen participation and load on A_{cw} for oil mill waste oil-camphor oil blend.

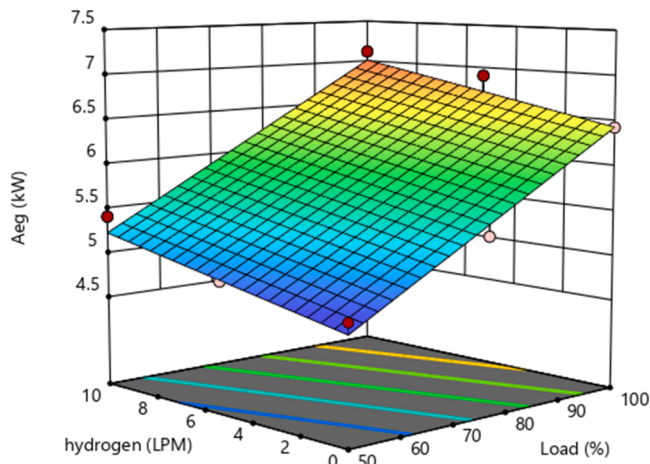


Fig. 24. Influence of hydrogen participation and load on Aeg for oil mill waste oil.

with air and the presence of hydrogen at the top cylinder, owing to its lower density and liquid fuel at the bottom side of the combustion chamber, provide more heat streak transfer uniformly at all places of the cylinder. Chaudhary et al. (2024). observed an increase in heat loss in the engine wall and coolant, similar to our cooling water exergy findings.

4.3.3. Engine exhaust exergy

Aeg indicates the exergy loss to the possible surroundings such as atmosphere through the exhaust gas, which is a matter of EGT, the temperature gradient between exhaust gas and atmosphere, and the flow rate of the exhaust gas.

4.3.3.1. Impact of hydrogen on Exergy rate of engine exhaust using oil mill waste oil. The Fig. 24 disclosed the details of A_{eg} deviation concerned with oil mill waste oil and hydrogen. The OM100 has an Aeg value of 6.42 kW when it is operating at its rated power, which is 7.22%, 6.97%, and 9.71% lower than diesel, the OM100H5, and the OM100H10 respectively. Oil waste from mills, a highly viscous fuel, contributes to poor spray characteristics and leads to higher heat in the atmosphere and surroundings. lending hydrogen by replacing the air molecules contributed to the higher exergy rate. The hydrogen that is present in the crevice volume and that is introduced during the suction stroke is brought back to the combustion chamber at the conclusion of the combustion process. This hydrogen is able to participate in the

combustion process owing to its improved diffusivity and wider spectrum of burning ability.

4.3.3.2. Impact of hydrogen induction on Exergy rate of engine exhaust using oil mill waste oil – camphor oil blend. The Fig. 25 manifests the details of A_{eg} deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. At rated power, Aeg value for OMC50 is found to be 6.7 kW that is 3.30% higher than diesel fuel but 4.22% higher than OM100. In mean time it is 7.84% and 10.34% lower than OMC50H5 and OMC50H10 respectively. Furthermore, in contrast to OM100, OMC50 points out the exergy rate of engine exhaust is substantially lower. The OMC50 experiences expansion cooling as a consequence of a higher expansion rate, which leads to a decline in the temperature of the exhaust gas. This is done in order to achieve a low viscosity and cetane rating. Consequently, the exergy rate of the engine exhaust experienced by OMC50 is reduced. The enhanced diffusivity of hydrogen, which is provided by OMC50 during the combustion process, helps to ensure that the air and fuel are well mixed. This is because hydrogen spreads out more uniformly than other substances. The combustion of blowby hydrogen is responsible for the increased contribution of heat that hydrogen makes during the later stages of the combustion process. Therefore, the presence of hydrogen causes an increase in the rate of exergy that is released. Gupta et al. (2025) noticed a downturn in exhaust exergy loss caused by an accelerated combustion rate, which reduces exergy loss via tailpipe emissions; this finding contradicts the existing data on exhaust gas exergy loss.

4.3.4. Exergy rate of destruction

Ad narrates the exergy loss in non-determined form, which is a function of the ability of systems to convert into measurable form. Theoretical perspective: it should be low as much as possible in order to retain the maximum possible energy in recoverable form.

4.3.4.1. Impact of hydrogen on Exergy rate of destruction using oil mill waste oil. The Fig. 26 conveys the details of Ad deviation concerned with oil mill waste oil and hydrogen. At full load conditions, the Ad value of OM100 is obtained as 13.03 kW, which is 16.77%, 4.91%, and 9.64% higher than diesel, OM100, OM100H5, and OM100H10, respectively. Even though OM100 has a high oxygen content and a lower stoichiometric air-fuel ratio, the increase in Ad is responsible for the lower heat release rate produced by the higher viscosity. The addition of hydrogen to combustion processes alongside air molecules and OM100 results in a faster heat release rate, which is due to hydrogen's higher heating value and instant rapid combustion properties. As a consequence, the ads for

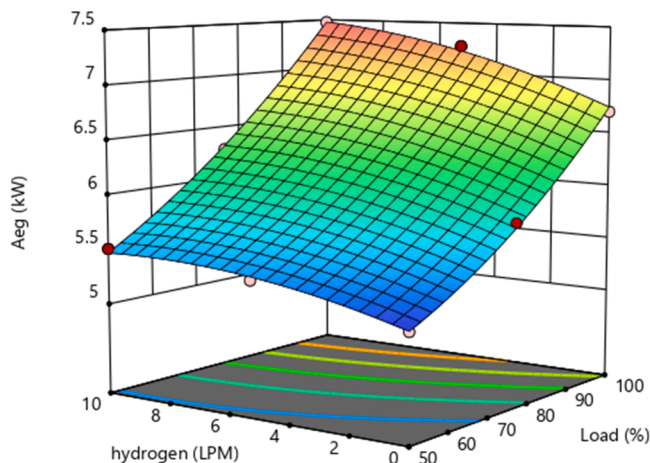


Fig. 25. Influence of hydrogen participation and load on Aeg for oil mill waste oil-camphor oil blend.

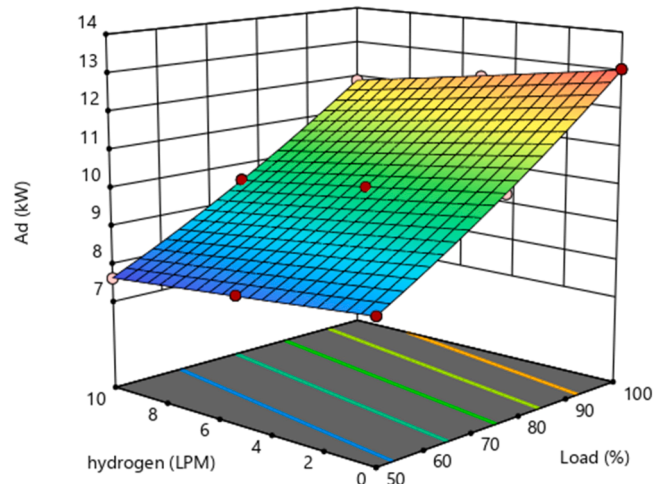


Fig. 26. Influence of hydrogen participation and load on Ad for oil mill waste oil.

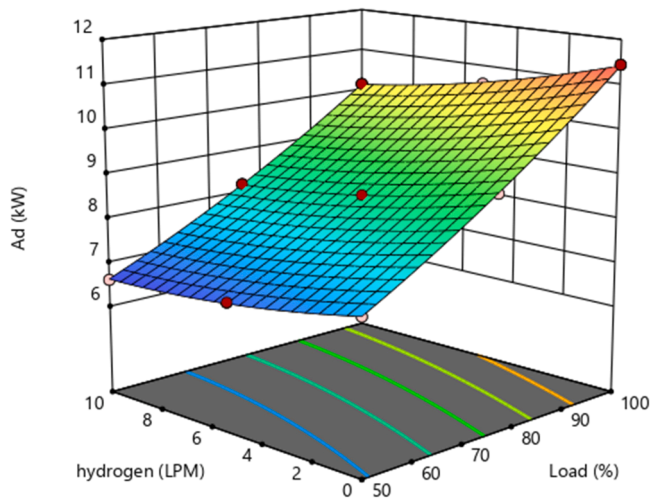


Fig. 27. Influence of hydrogen participation and load on Ad for oil mill waste oil-camphor oil blend.

OM100H5 and OM100H10 were withdrawn.

4.3.4.2. Impact of hydrogen induction on Exergy rate of destruction using oil mill waste oil – camphor oil blend. Fig. 27 expresses the details of Ad deviation concerned with an oil mill waste oil-camphor oil blend and hydrogen. The OMC50 has an Ad value of 11.44 kW at rated power, which is 12.23% less than the OM100 but 2.4%, 7.97%, and 12.65% greater than the diesel, OMC50H5, and OMC50H10. Ad is found to be lower for OMC50 compared to OM100 as a result of lower entropy generation due to the merit of improvised premixed combustion. Although hydrogen has a higher auto-ignition temperature and a higher stoichiometric air-fuel ratio because of its properties, such as instant combustion attributes, higher diffusivity, a higher flame temperature, and a high flame speed, it lowers the Ad. Therefore, affording the hydrogen with OMC50 declines the Ad. Similar to our findings, Bayramoğlu et al. (2025), observed a decrease in destructed energy as a consequence of an increase in exhaust energy due to the effective participation of hydrogen at all stages of combustion.

4.3.5. Entropy generation

EG represents the level of wastefulness in energy conversion, which depends on how much exergy is lost and the surrounding temperature

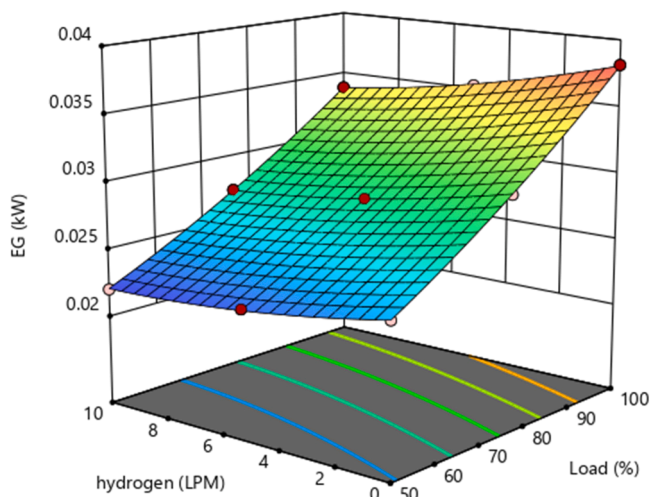


Fig. 28. Influence of hydrogen participation and load on EG for oil mill waste oil.

during these processes. From a theoretical standpoint, it should be as low as possible to allow systems to better convert available fuel into useful output. As per the theoretical point of view, it should be as low as possible so that systems might have more opportunities to convert the fuel availability into useful output.

4.3.5.1. Impact of hydrogen on Entropy generation using oil mill waste oil.

The Fig. 28 conveys the details of EG deviation concerned with oil mill waste oil and hydrogen. With an EG value of 0.043 kW/K at rated power, the OM100 is 9.01%, 22.090%, and 18.26% greater than the diesel OM100H5 and OM100H10, respectively. OM100 has the highest EG as a result of higher irreversibility caused by the higher unaccounted loss or non-recoverable heat energy loss. When hydrogen is used in conjunction with OM100, EG falls owing to effective energy transfer as a result of hydrogen's benefits, which leads to larger energy transfers to engine cooling water and exhaust. The addition of hydrogen promotes homogeneous combustion processes and generates instantaneous heat energy, increasing the OM100's burn rate. As a result, it contributes to reduced energy loss.

4.3.5.2. Impact of hydrogen induction on Entropy generation using oil mill waste oil – camphor oil blend.

The Fig. 29 describes the details of EG deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. The OMC50 has an EG value of 0.0381 kW/K under full load operating settings, which is 12.23% less than the OM100 but 2.49%, 7.97%, and 12.65% greater than the diesel, OMC50H5, and OMC50H10. From the EG values, it is found that OMC50 has the lower EG compared to OM100. OMC50, low-viscosity fuel, gets the benefits from the good spray characteristics owing to amend atomization. OMC50, lower cetane rating fuel, possesses an extended delay period and accesses a large amount of fuel in premixed combustion, which ensures more energy transfer to the piston. On the whole, OMC50 has a lower EG compared to OM100. Enhancing combustion using hydrogen fuel, due to the advantageous acceleration of oxidation processes, improves energy transmission to the environment, cooling water, and the flywheel. Consequently, it minimizes the EG under all loading circumstances. Paneerselvam and Ganapathy (2024) noted the drop in the entropy generation like our results owing to decrement in cyclic irreversibility.

4.3.6. Exergy efficiency

ExE indicates the energy conversion efficiency in terms of maximum possible theoretical energy. As per the thermodynamic point of view, exergy efficiency should be as high as possible.

4.3.6.1. Impact of hydrogen on Exergy efficiency using oil mill waste oil.

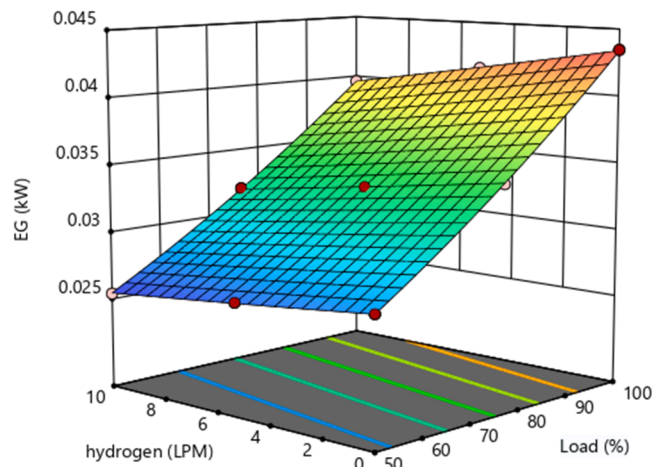


Fig. 29. Influence of hydrogen participation and load on EG for oil mill waste oil-camphor oil blend.

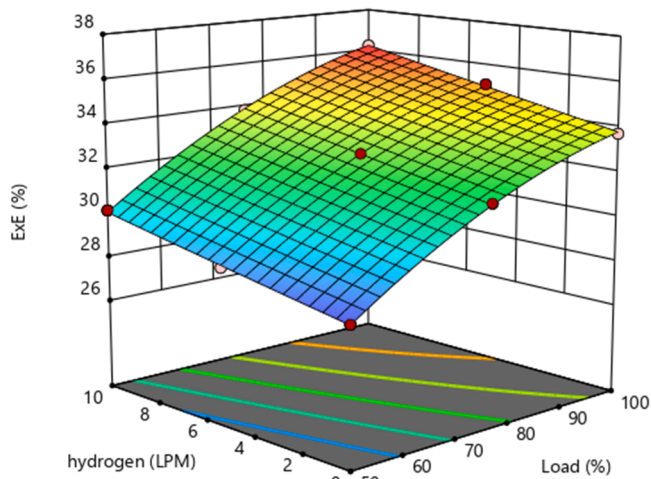


Fig. 30. Influence of hydrogen participation and load on ExE for oil mill waste oil.

Fig. 30 illustrates the specifics of ExE variation related to waste oil from oil mills and hydrogen. ExE is a crucial measure utilised to evaluate the thermodynamic performance of fuel during cyclic operations. Despite OM100 having favourable oxygen content, a reduced stoichiometric air-fuel ratio, and an adequate cetane rating, it exhibits the lowest ExE due to inefficient energy transfers caused by elevated viscosity. As long as the hydrogen possesses the higher heating value and good diffusivity rate, it is anticipated for the higher oxidation rate unless the hydrogen suffers from the poor breathing ability during the combustion processes. Lending hydrogen along with OM100 speeds up the oxidation rate by raising the peak pressure and temperature. Therefore, with the help of the instant combustion attributes of hydrogen, ExE is improved for OM100.

4.3.6.2. Impact of hydrogen induction on Exergy efficiency using oil mill waste oil – camphor oil blend. The Fig. 31 describes the details of ExE deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. Any fuel – it is mandatory to get the higher ExE to suggest a good alternative fuel. In this aspect, the OMC50 shows a higher ExE compared to the OM100. OMC50 is in a position to get the higher ExE as a result of lower viscosity, which supports the preparation of excellent air-fuel mixtures and a low cetane rate, which amends the heat release rate. Affording the hydrogen with OMC50 further emends the combustion processes with its fuel properties. Increased diffusivity enables

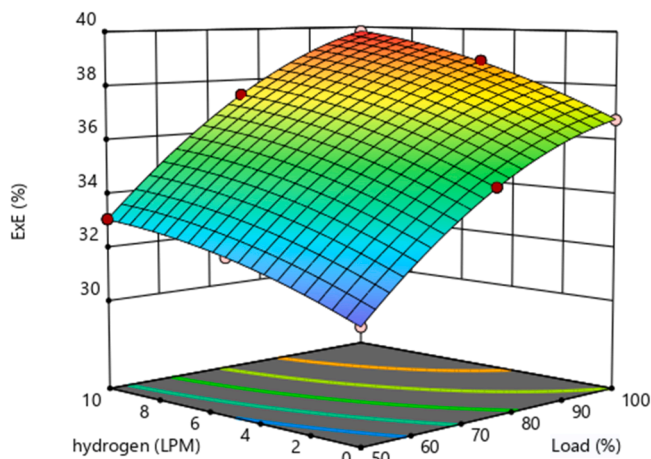


Fig. 31. Influence of hydrogen participation and load on ExE for oil mill waste oil-camphor oil blend.

hydrogen to locate the oxygen concentration and create a homogeneous air-fuel mixture at several localised regions inside the combustion chamber. The elevated heating value and instant combustion characteristics of hydrogen provide a greater fuel combustion under premixed conditions, hence augmenting the peak pressure. Consequently, the oxidation rate and energy transfer escalate. Consequently, supplying hydrogen with OMC50 enhances the ExE. Bawne et al. (2026) experienced an increase in exergy efficiency, similar to our findings, attributed to the efficient use of hydrogen.

4.3.7. Sustainability index

Sustainability index (SI) is a non-dimensional vital parameter that analyze the system's sustainability in relationships of a thermodynamic perspective. Therefore, SI should be higher, as much as possible, like the ExE.

4.3.7.1. Impact of hydrogen on Sustainability index using oil mill waste oil. The Fig. 32 explains the details of SI deviation concerned with oil mill waste oil and hydrogen. When the OM100 is operating under full load circumstances, its specific impulse (SI) is 1.508, which is 5.40%, 2.07%, and 3.79% lower than diesel, OM100H5, and OM100H10, respectively. The higher viscosity of OM100 is responsible for the slower oxidation processes, which in turn leads to a poor energy release rate throughout the cyclic cycles it undergoes. The higher viscosity of OM100 results in poor spray characteristics, which in turn leads to inadequate air-fuel mixing and poor air-fuel mixture formation, which in turn enables a greater amount of fuel to be used in the performance of the power generation process. As a result, the SI for OM100 is lower than the SI for the other fuels that were considered for testing. There are a number of benefits associated with hydrogen that contribute to an increase in the SI. These benefits include a greater heating value, quick combustion characteristics, a higher diffusivity, a broad flammability range, higher operational combustion products temperature and speed, and support for improved energy transfers.

4.3.7.2. Impact of hydrogen induction on Sustainability index using oil mill waste oil – camphor oil blend. The Fig. 33 elucidates the details of SI deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. At full load, OMC50H10 has a SI of 1.66, which is 4.19%, 10.14%, 5.108, and 1.75% greater than diesel, OM100, OMC50, and OMC50H5. Because of its efficient energy transfer mechanism, OMC50 has a greater SI than OM100. Despite having a lower cetane rating, OMC50 burns the accumulated fuel over a longer delay period, accelerating the rate of heat transmission and oxidation. Energy transmission

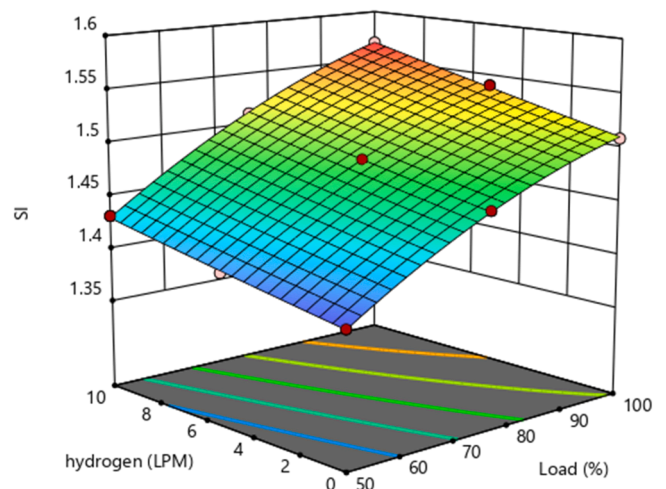


Fig. 32. Influence of hydrogen participation and load on SI for oil mill waste oil.

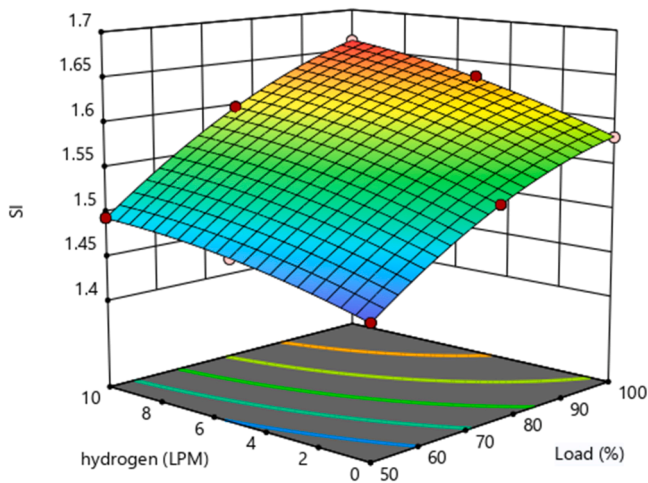


Fig. 33. Influence of hydrogen participation and load on SI for oil mill waste oil-camphor oil blend.

is accelerated by adding hydrogen to combustion processes. Both the preflame and postflame processes are supported by the hydrogen providing. It now offers a greater SI than OMC50. Because of its efficient energy transfer mechanism, OMC50 has a greater SI than OM100. Singh et al. (2025), observed an upsurge in SI similar to our findings due to a decrease in irreversibility and exergy losses.

4.4. Economic characteristics

This part talks about economic factors by focusing on the losses related to temperature, energy, and the environment. It is important to know how economic factors were used to lower the loss during the energy exchange processes. So, TEL, ExEL, and EnEL are examined at in this phase.

4.4.1. Thermoeconomic loss

TEL indicates economics linked to the energy loss during the cyclic processes. It is collective energy loss during the cyclic process or energy conversion processes. Therefore, TEL should be minimum during the cyclic processes.

4.4.1.1. Impact of hydrogen on thermoeconomic loss using oil mill waste oil. The Fig. 34 narrates the details of TEL deviation concerned with oil mill waste oil and hydrogen. TEL of OM100 shows the highest value for energy loss owing to the non-measurable form of energy availability during the cyclic processes. TEL of 0.001449 kW/\$ has been calculated for the OM100 when it is working under full load conditions. When compared to diesel, OM100H5, and OM100H10, respectively, this represents an increase of 60.95%, 18.43%, and 39.98% that is accordingly higher. It has been noted that the TEL for OM100 is higher than that of other testing settings. This is because the increased viscosity results in a slower burning rate, which in turn causes the TEL to be higher. Consequently, it results in a lower in-cylinder peak pressure and temperature. This is because the increased viscosity causes the combustion process to proceed more slowly. It has an impact on the energy transfer to the piston and the heat transfer to the engine cooling water to promote slower combustion. On the whole, due to the constant speed operations, possibilities for the energy transfers also reduced and elevated the irreversibility of the cycle. Hydrogen in the air intake manifold promotes homogeneous air-fuel mixes. Hydrogen with a higher-octane rating and heating value may aid energy transfer during premixed combustion. Hydrogen's high diffusion and flammability increase energy transfer after burning. Overall, hydrogen induction improved energy transfer and lowered TEL.

4.4.1.2. Impact of hydrogen induction on thermoeconomic loss using oil mill waste oil – camphor oil blend. The Fig. 35 describes the details of TEL deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. The TEL of the OMC50H10 is estimated to be 0.00071 kW/\$ while operating under full load circumstances. This is a 21.403%, 51.16%, 25.27%, and 11.15% increase in comparison to the diesel, OM100, OC50, and OC50H5 respectively. OC50 exhibits excellent energy transfer during the early stages of combustion (premixed combustion). As a result, the TEL for OC50 is considerably smaller than that of OM100. Introducing hydrogen into the air intake manifold significantly enhances the creation of homogeneous air-fuel mixes. The elevated octane rating and heating value of hydrogen may enhance energy transfer during premixed combustion processes. The elevated diffusion rates and significant flammability of hydrogen facilitate energy transfer during post-combustion processes. The energy transmission was enhanced via hydrogen induction, resulting in a reduction of the TEL.

4.4.2. Exergoeconomic loss

ExEL conveys the economic loss connected to the exergy loss as a

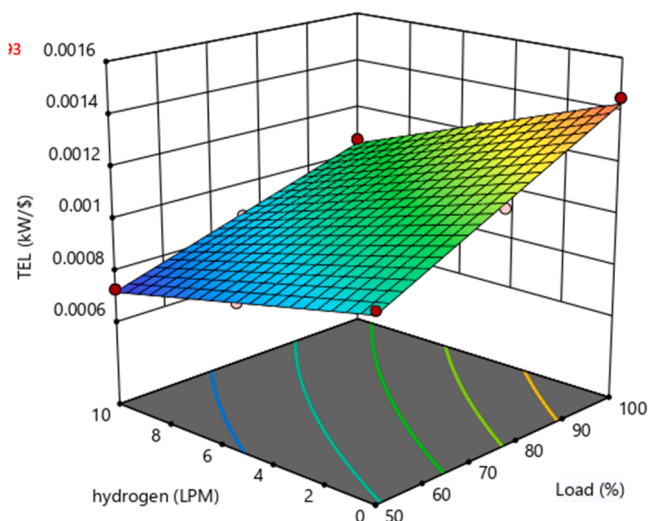


Fig. 34. Influence of hydrogen participation and load on TEL for oil mill waste oil.

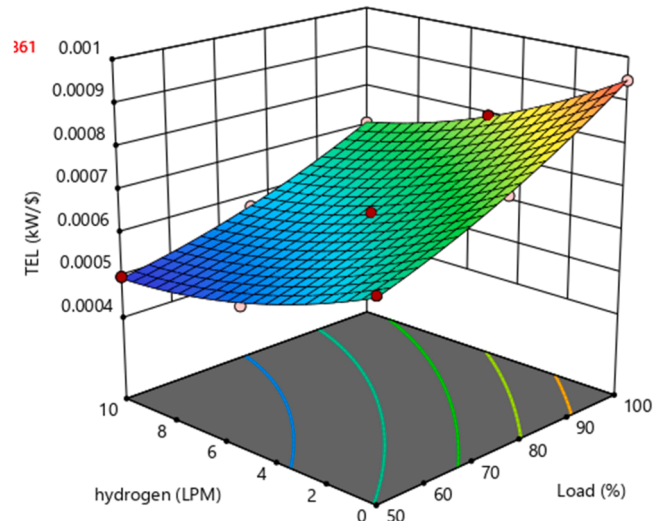


Fig. 35. Influence of hydrogen participation and load on TEL for oil mill waste oil-camphor oil blend.

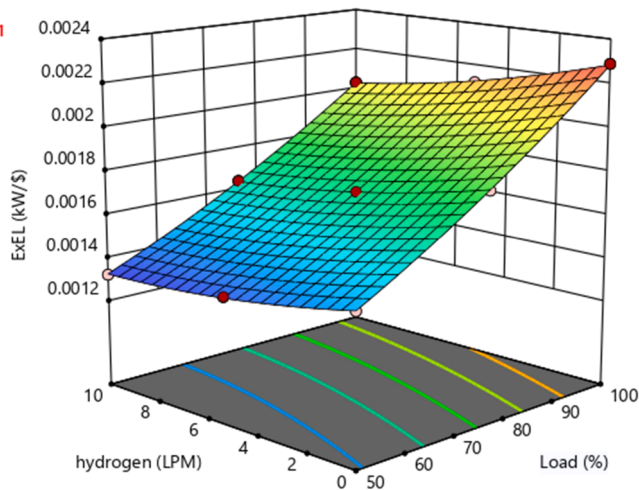


Fig. 36. Influence of hydrogen participation and load on ExEL for oil mill waste oil.

matter of energy conversion processes. Henceforth, ExEL should be low so that systems can use the energy during the cyclic processes.

4.4.2.1. Impact of hydrogen on Exergoeconomic loss using oil mill waste oil. The Fig. 36 depicts the features of ExEL caused by hydrogen induction when the engine is fueled by the OM100. At full load, the OM100 has an ExEL of 0.002608 kW/\$, which is 16.77%, 4.91%, and 9.64% higher than the diesel, OM100H5, and OM100H10. OM100 has elevated ExEL due to the following factors. The reduced oxidation rate of OM100 decreases the combustion peak temperature, so diminishing the temperature difference between the combustion gas next to the cylinder wall and the cylinder wall itself, which impedes energy transmission to the cylinder border. The prolonged combustion duration increases exhaust gas temperature, which may facilitate energy transmission; however, it also heightens energy loss due to irregularities in energy transfer.

4.4.2.2. Impact of hydrogen induction on Exergoeconomic loss using oil mill waste oil – camphor oil blend. The Fig. 37 shows the differences in ExEL for the fuel OC50 with and without hydrogen induction. The OC50 has an ExEL of 0.002289 kW/\$ at rated load, which is higher than diesel, OC50H5, and OC50H10 by 2.49%, 7.97%, and 12.65%, respectively, but lower than OM100 by 12.23%. In comparison to OM100, OMC50

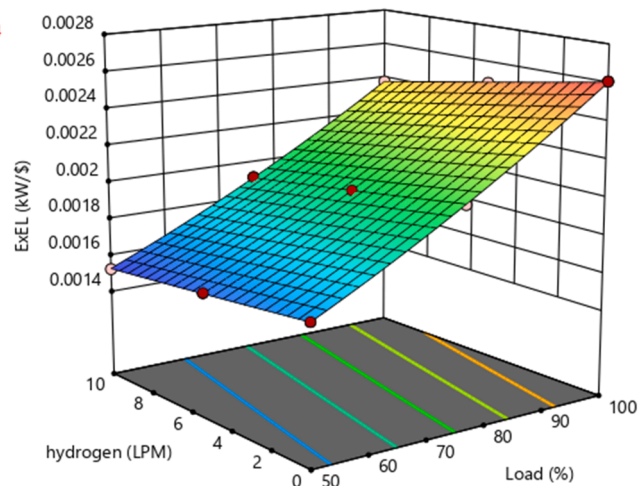


Fig. 37. Influence of hydrogen participation and load on ExEL for oil mill waste oil-camphor oil blend.

exhibits reduced entropy formation and diminished exergy destruction, attributable to superior air-fuel mixture preparation facilitated by its lower viscosity and cetane number, which enhance heat creation during premixed combustion processes. OC50 shows lower destructed exergy and entropy generations than OM100, confirming its reduced ExEL due to improved energy transfer mechanisms.

The provision of hydrogen facilitates the construction of homogeneous air-fuel mixtures, while its elevated octane rating promotes instantaneous combustion, accelerates oxidation processes, and generates combustion gases that transmit energy to the piston cylinder. Moreover, the presence of hydrogen enhances heat transport and energy dissipation in engine exhaust. Consequently, hydrogen impedes energy loss in non-recoverable forms and reduces the ExEL.

The presence of hydrogen aids energy transmission and enables enough energy transfer. As a result, the ExEL for OC50H5 and OC50H10 is lower.

4.4.3. Enviroeconomic loss

Enviroeconomic loss (EnEL) is an environmental parameter that analyses the money spent on the preservation of the environment due to the utilization of fuels in the systems. In connection with the economy and environment, EnEL should be as low as possible so that environmental safety can be maintained.

4.4.3.1. Impact of hydrogen on enviroeconomic loss using oil mill waste oil. The Fig. 38 conveys the details of EnEL deviation concerned with oil mill waste oil and hydrogen. At maximum load conditions, EnEL for diesel is 0.485 \$/day, which is 18.50%, 15.40%, and 12.08% lower than OM100, OM100H5, and OM100H10. OM100 exhibits elevated EnEL due to its increased carbon content, resulting in a greater quantity of carbon atoms during combustion, which therefore produces higher BSCO₂ emissions. The viscosity of OM100 is expected to result in reduced BSCO₂ emissions due to the inadequate preparation of air-fuel mixes caused by its greater viscosity. However, EnEL findings reveal that BSCO₂ emissions mostly rely on the quantity of carbon atoms engaged in the combustion processes.

4.4.3.2. Impact of hydrogen induction on Enviroeconomic loss using oil mill waste oil – camphor oil blend. Fig. 39 describes the details of EnEL deviation concerned with oil mill waste oil-camphor oil blend and hydrogen. The EnEL of OC50 is 0.54 \$/day, which is 11.37%, 4.47%, and 9.13% more than diesel, OC50H5, and OC50H10 at full load. It is presumed that the reduced viscosity of OC50 results in a higher EnEL than that of OM100. However, the results indicate the opposite trend.

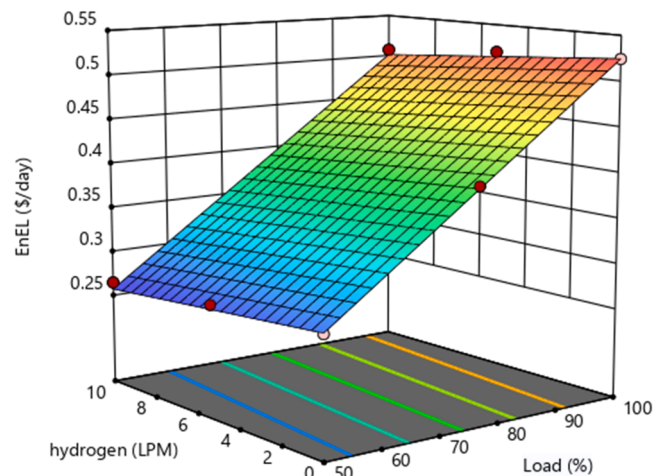


Fig. 38. Influence of hydrogen participation and load on EnEL for oil mill waste oil.

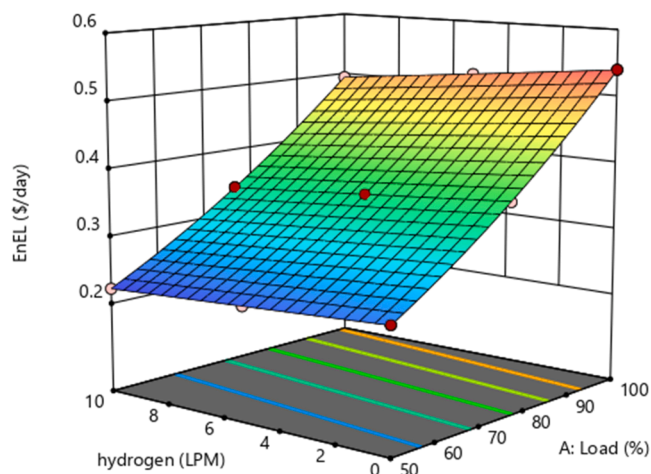


Fig. 39. Influence of hydrogen participation and load on EnEL for oil mill waste oil-camphor oil blend.

The amount of carbon that is present in the fuel has a significant impact on EnEL. Because of the lower carbon level, OC50 has a lower EnEL than OM100 does. This is because of the lower carbon content. On the other hand, the OMC50 has a lower cetane rating, a lower viscosity, and a fuel build oxygen content, all of which contribute to improved energy transfer and a reduction in the quantity of carbon dioxide that is released per kilogram of fuel. Because of the negative characteristics of hydrogen (such as its poor breathing capacity and higher-octane rating) and camphor oil (which has a lower cetane rating), it is anticipated that the presentation of hydrogen with OMC50 would result in the generation of increased emissions. On the other hand, the findings that were obtained demonstrate that the aforementioned drawbacks of hydrogen and camphor oil do not have an impact on the final result of the EnEL emissions. Even so, it improves the performance of the CI engine while simultaneously reducing the pollutants.

5. Conclusions

The following conclusion was obtained for the experiment conducted with a CI engine powered with oil mill waste oil and an oil mill waste oil-camphor oil blend with hydrogen as a secondary fuel.

- The viscosity of OM100 is high, which results in poor combustion characteristics. It also produces greater levels of BSCO, BSCO₂, BSCO, and smoke emissions, although it has lower levels of BSNO, BTE, ExE, and SI when compared to diesel fuel. Furthermore, in comparison to OMC50, OM100 has a greater TEL, ExEL, and EnEL respectively.
- The combination of camphor oil and waste oil from oil mills results in a reduction in emissions such as BSHC, BSCO₂, BSCO, and smoke opacity, while simultaneously increasing the ExE, SI, and BTE numbers. The TEL, ExEL, and EnEL decrease as a result of the improved premixed combustion processes brought about by the OMC50's lower cetane rating.
- 3. The incorporation of hydrogen into OM100 speeds up the oxidation processes and makes it possible for the activities concerned with energy transfer to take place correctly. This ultimately leads to an increase in the BTE, ExE, and SI.
- Presenting hydrogen with OMC50 increases BTE, Ad, Aeg, Acw, ExE, SI, and BSNO. On the other hand, it decreases smoke opacity, BSHC, BSCO, BSCO₂, TEL, EnEL, and ExEL.
- Utilizing the waste oil from the oil mill as fuel for CI engines shows that biomix oil is a viable substitute. Waste oil from oil mills may

provide useful results when combined with carbon-free hydrogen fuel and low-carbon camphor oil.

- The current findings are constrained by elevated BSNO emissions. Consequently, contemporary research may be augmented in the realms of BSNO emissions reduction by the selective catalytic reduction method and the exhaust gas recirculation technologies.

CRediT authorship contribution statement

Ferzat Anka: Visualization, Validation. **Utku Kale:** Supervision, Formal analysis. **Edwin Geo Varuvel:** Writing – review & editing, Project administration. **JS Femilda Josephin:** Visualization, Validation, Software. **Artūras Kilikevičius:** Writing – review & editing, Validation, Project administration. **Jonas Matijosius:** Writing – review & editing, Supervision. **Manikandaraja Gurusamy:** Methodology, Formal analysis. **Mathanraj Vijayaragavan:** Investigation, Formal analysis. **Siva-shankar Manickam:** Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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