



# Enhanced combustion and emission characteristics of diesel-algae biodiesel-hydrogen blends in a single-cylinder diesel engine

Hariram V<sup>a,\*</sup>, Sathishbabu R<sup>b</sup>, Godwin John J<sup>c</sup>, Nandagopal Kailiappan<sup>d,e,\*</sup>, Vijayakumar K<sup>f</sup>, Sangeeth Kumar E<sup>g</sup>, Kamakshi Priya K<sup>h</sup>

<sup>a</sup> Department of Mechanical Engineering, Hindustan Institute of Technology and Science, Padur, Chennai, Tamil Nadu, India

<sup>b</sup> Department of Mechanical Engineering, VSB College of Engineering Technical Campus, Coimbatore, Tamil Nadu, India

<sup>c</sup> Department of Mechanical Engineering, Rajalakshmi Institute of Technology, Chennai, Tamil Nadu, India

<sup>d</sup> Department of Mechanical Engineering, Haramaya Institute of Technology, Haramaya University, Dire Dawa, Ethiopia

<sup>e</sup> Department of Food Technology, Dhanalakshmi Srinivasan College of Engineering, Coimbatore, Tamilnadu, India

<sup>f</sup> Department of Mechanical Engineering, Aarupadai Veedu Institute of Tech., Paiyanur, Tamil Nadu, India

<sup>g</sup> Department of Automobile Engineering, Hindustan Institute of Technology and Science, Padur, Chennai, Tamil Nadu, India

<sup>h</sup> Department of physics, Saveetha School of Engineering SIMATS, Saveetha University, Chennai, Tamilnadu, India

## ARTICLE INFO

### Keywords:

Biodiesel  
Combustion  
*Dunaliella salina*  
Emission  
Hydrogen

## ABSTRACT

With the escalating global energy demand, the pursuit of sustainable energy sources has become increasingly urgent. Among these, biofuels have gained significant attention for their potential to provide renewable and eco-friendly alternatives. Biodiesel is recognized for its diverse and cost-effective feedstock options. The study provides a novel approach to the production of biodiesel by employing the use of *Dunaliella salina* microalgae as a green source. The research suggests the blends provide a future solution to less toxic fuel sources, achieving efficiency and minimizing emissions. This research emphasizes on the production of biodiesel from *Dunaliella salina* microalgae, a promising resource due to its high energy yield. The microalgae were cultivated in an f/2 nutrient medium enriched with carbon dioxide, vitamins, and trace metals. A total of 700 mL of bio-oil was extracted using ultrasonication at 50 Hz for 85 minutes. Then, the bio-oil was transesterified in a single-stage, sodium hydroxide-catalysed process with methanol as a solvent. The process yielded a high extraction efficiency of 94 %. The produced biodiesel was characterized through advanced analytical techniques, including NMR spectroscopy, GC-MS, and FTIR test studies, confirming its suitability as a fuel. Combustion and emission analyses revealed that the direct substitution of biodiesel blends for diesel in engines significantly reduced hydrocarbon and carbon monoxide emissions, although a slight increase in nitrogen oxide (NO<sub>x</sub>) emissions was noted. The combustion and emission characteristics were influenced by blend composition and calorific value. Additionally, the study provides a detailed comparison of the performance of pure diesel, biodiesel blends, and hydrogen-enriched biodiesel in diesel engines, offering valuable insights into their environmental and performance impacts. This study gives additional insights towards future work such as scalability (consisting large scale cultivation of algae for better studies), engine durability (studies on engine wear and tear) and integration with renewable energy sources (integrating renewable sources like solar and wind energies).

## 1. Introduction

The focus of current regulations is primarily on reducing emissions of carbon dioxide and other harmful pollutants in order to mitigate climate change. The primary source of greenhouse gas emissions from vehicles is human activity, specifically the combustion of conventional fuels, which have a high carbon content and produce significant hydrocarbon

emissions. Therefore, the growth of sustainable alternatives to fossil fuels is becoming more important. Compared to conventional feedstock's, algae can produce more biodiesel per unit of growth area because of their high lipid content (up to 70 %). The ability of algae to absorb carbon dioxide is approximately ten times greater than that of land-based plants, which contributes to the algae's increased environmental sustainability. Algal biodiesel's appeal is increased by its

\* Corresponding authors.

E-mail addresses: [connect2hariram@gmail.com](mailto:connect2hariram@gmail.com) (H. V), [nandagopal.kaliappan@haramaya.edu.et](mailto:nandagopal.kaliappan@haramaya.edu.et) (N. Kailiappan).

<https://doi.org/10.1016/j.rineng.2025.104676>

Received 31 January 2025; Received in revised form 27 February 2025; Accepted 18 March 2025

Available online 19 March 2025

2590-1230/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

capacity to produce useful by-products, maintain biodiversity, and need less resources [1]. The process of making biodiesel involves interacting oils and alcohol stoichiometrically to produce glycerol and biodiesel (methyl ester). Because it can run diesel engines more reliably than petroleum, regardless of environmental concerns [2]. Blending it in variable ratio with neat diesel fuel can lead to better combustion compared to petroleum-based diesel due to its high flash point, oxygen concentration and cetane number. More than 300 oil-bearing crops have been identified as possible global sources for the production of biodiesel. Ramadhas et al. [3] adopted both one and two step transesterification to convert rubber seed oil with high FFA to biodiesel. In the first stage, a molar ratio of 6:1 concentration of KOH as a catalyst at a reaction temperature of about 45°C and a reaction time of 30 minutes gave the highest biodiesel yield, and a 0. The result obtained depicted that the maximum reduction of FFA content was obtained with 5 % H<sub>2</sub>SO<sub>4</sub> catalyst. It is therefore clear that biodiesel had relatively high viscosity, slightly lesser calorific value and a rather higher flash point than the diesel [4] analysed the effect of *Jatropha* methyl ester before and after oxidation. They looked at the analysis based on the activation energy. The results showed that there was a considerable decrease in the size of the carbon smoke particles and a steady decrease in CO emission following oxidation [4] analysed the biodiesel blends in the engine considering the emission and performance parameters. The benchmark was verified using both experimental and numerical analysis. Renewable fuels, such as bio-oil, biodiesel, bioethanol, and biogas, are being considered for direct use or blending with regular diesel in the future. This will likely lead to lower emissions and a greener energy landscape [5].

The pressing need to address climate change is reflected in the tightening rules on CO<sub>2</sub> and other pollutant emissions. Greenhouse gas emissions which is a main human caused emission due to conventional fuels usage in automobiles. Because traditional fuels contain more carbon, when they burn, they release a lot of CO<sub>2</sub>. As a result, attention is now being focused on creating sustainable fuel substitutes. Blending renewable fuels with conventional fuels, such as bio-oil, biodiesel, bioethanol, and biogas, is a viable alternative. Blends of biodiesel and diesel are predicted to be widely used in the future, contributing to a decrease in overall emissions [6]. The lipids from deceased plants and animals were used to make bio-oil. Traditionally, feedstock is primarily composed of animal fats and vegetable oils. It could not be heated as well and was more viscous. Therefore, more processing was needed before biodiesel could be made from it. In tests of combustion, biodiesel fared better than raw bio-oil. Biodiesel has a higher heating value, is non-toxic, and is renewable [7].

Biodiesel plays a major role in mechanical industry in order to determine the alternate fuel for the compression ignition engine. Widely researchers work with vegetable oils and third generation algal oils [7–9]. Vegetable based biodiesel possess numerous benefits on comparison with conventional diesel, including as a higher flash point and Cetane number, reduced sulfur with better lubricating qualities. But compared to diesel, it has more viscosity due to its fatty acid content, which might impair cold flow characteristics and clog fuel filters. Compared to biodiesel made from animal fat, biodiesel made from vegetable oil has superior cold flow characteristics. Furthermore, the molecular makeup of biodiesel influences emissions and combustion efficacy in diesel engines, underscoring the significance of fuel composition in engine performance. Anish et al., [10] analysed the biodiesel produced from *Parinari polyandra* oil usage in diesel engine. It has been found that the defined fuel's qualities are a lot more similar to diesel fuel. The power and thermal efficiency data indicated that the B10 mix was the best option.

Hydrogen enriched biofuels combined with RCCI technology is a cost-efficient alternative for conventional fuel, addressing cost and pollution concerns. The fuel blend of 65 wt. % of waste leather fat oil and 35 wt. % of ammonium hydroxide reduced NOx levels by 9.2 %, hydrocarbons by 27 %, and smoke by 26 % without compromising

engine efficiency. The cost-benefit ratio showed a reduction in fuel cost by 25.6 %, which is an economical and sustainable solution as stated by [11,12] studied about Acetylene fumigation using lychee seed biodiesel in a dual-fuel engine showed a substantial increase in brake thermal efficiency (28.98 % for 2 LPM and 46.54 % for 4 LPM). The fumigation of acetylene using LSB lowered CO<sub>2</sub> (25.71 %), CO (72.4 %), HC (33.33 %), and smoke (36.59 %) levels, though it enhanced NOx emissions (57.48 %). This paper emphasized LSB-acetylene blend as a potential alternative for a sustainable diesel fuel addressing concerns related to emissions.

Hydrogenated biodiesel (HB) holds promise for reducing urban air pollution, fossil fuel consumption, and global warming. However, it tends to produce trans-isomers rather than cis-isomers, leading to higher kinematic viscosity and cold flow issues due to crystallization. Partial hydrogenation increases pour point and cloud point temperatures but improves combustion consistency, reducing engine vibration. This process, accelerated by a catalyst, enhances biodiesel quality and combustion properties. The choice of catalyst depends on the biodiesel properties and reactor type. While higher hydrogen concentrations speed up hydrogenation, reaction temperature has minimal effect, though prolonged processing impacts oxidation stability [13,14].

Emissions play a vital role in engine study where polycyclic aromatic hydrocarbon (PAHs) are not only hazardous but are also associated with issues such as wet stacking in the engine. Biodiesel (B100), with no aromatics, reduces PAH emissions (by ~48–49 %) and PAH toxicity (by ~83–85 %) in significant amounts in comparison with diesel (D100). Engine design is also a parameter in which PAH reduction is improved in the Kubota engine due to its combustion system [15]. A comparative study of *Isochrysis aff. galbana* and *Scenedesmus dimorphus* algae for biodiesel production was studied by Alpaslan 2020 where, *Isochrysis aff. galbana* had a higher percentage of lipids (42.65 % compared with 15.87 %) and a higher transesterification rate (94.6 % compared with 87.4 %), and was a better biodiesel source.

Research pursued in this study is that *Dunaliella salina* algae-based biodiesel was synthesized, standardized, and subsequently utilized in a study on combustion as well as emissions in a diesel engine. To mitigate some of its combustion challenges that included poor combustion as well as excessive emissions of nitrogen oxide (NOx), hydrogen fuel was introduced in a bid to enhance combustion efficiency as well as reduce noxious emissions. The effect of hydrogen induction on combustion performance as well as its emissions profile was thoroughly assessed.

Regardless of extensive research into a more sustainable alternative in the form of biodiesel, it is highly with challenges that involve higher emissions of nitrogen oxide (NOx) as well as reduced combustion efficiency over traditional fuel sources. These limitations hinder its full potential as a direct replacement in diesel engines without additional modifications. While previous studies have focused on optimizing biodiesel production, improving its properties through various feedstocks, and refining transesterification processes, there remains a significant gap in understanding how hydrogen induction can synergistically reduce emissions and enhance combustion in biodiesel-powered engines. Specifically, microalgae-based biodiesel, particularly from *Dunaliella salina*, has been underexplored in terms of its performance when combined with hydrogen fuel. Most existing research centers on feedstock optimization, with limited focus on real-world application challenges such as emissions control and engine performance in internal combustion engines. This study addresses this gap by investigating the dual impact of hydrogen addition on emissions reduction and combustion efficiency, providing valuable insights into how biodiesel can be optimized for both environmental sustainability and operational performance in practical engine applications.

## 2. Materials and methods

Microalgae can prove to be a most cost justifying alternative source of fuel from fossil fuel as well as can contribute towards lowered

production of greenhouse gas. Microalgae are those organisms that are highly endowed with a photic activity. Not merely in growth in terms of lipids, this is also a productive activity as a highly effective activity in terms of carbon sequestration as well as production of oxygen. The rate of growth as well as biological as well as biochemical contents can be altered by algae in varying states of a physio-chemical nature. A range of species of microalgae are cultivated at varying points in time in order to produce industrial, pharmaceutical as well as fuel. Among these species, a species known as *Dunaliella salina* is a species that is highly endowed with high lipid accretion. *Dunaliella salina* is endowed with a range of competent attributes that are appropriate in terms of production in terms of biodiesel. The cells in the species *Dunaliella* do not have a cellulose wall; in addition, a range of laboratory methods utilized in order to examine intercellular functions are more laborious in order to conduct on cells with a thick cell wall.

*Dunaliella salina* is a unicellular greenish-orange halophilic microalga that lives in the normal saline conditions. The species belongs to the family of Dunaliellaceae, Order Chlamydomonas, Class Chlorophyceae, and Division Chlorophyta. *Dunaliella salina* is of great interest and of potential applications in biotechnology and nutrition mainly because of its exceptional biomass, both rich in carotenoids and lipids, as well as for the well-known fact about its ability to grow at very high salinity. Above said alga is the one which had been chosen for this research, from which the biodiesel is to be extracted, which was obtained from National Institute of Ocean Technology, Chennai. As exposed by the literature study, in comparison with feedstocks, *Dunaliella salina* is associated with a more environmentally friendly and economically feasible and viable option for the production of biodiesel. It is a better option from an environmental and economic viewpoint because it has more lipid content, tolerance to harsh growing conditions, minimum resource requirements, and the possibility of producing co-products [16].

### 2.1. Extraction of Bio-oil from *Dunaliella salina* and its transesterification

The ultrasonication bio-oil extraction procedure was adopted on biomass obtained for *Dunaliella salina*. The algal oil was gained from it. To perform the ultra-sonication extracting procedure, its efficiency will be enhanced by mixing 100 g biomass of *Dunaliella salina* with 30 mL methanol, double-distilled water, and chloroform in ratio 1: 0.7: 2. The membranes of *Dunaliella salina* cell walls ruptured and the algal oil as a result floated out as ultrasonicator operated at 60 Hz frequency for 90 minutes. Sediment and gained oil shifted into a beaker later on and 10ml methanol poured in order to achieve them in order to mix nicely. Whatman filter paper was finally adopted in order to eliminate unwanted particles from algal oil [17]. In order to eliminate trace amount of H<sub>2</sub>O from gained algal oil, 6 mL acetone was adopted and heated. Ultimately, bio-oil gained from *Dunaliella salina* had 650 mL of oil (Fig. 1).

When it was tested, free fatty acid level in the bio oil was less than 2 %, Bio oil from *Dunaliella salina* can be transesterified into corresponding mono alkyl methyl esters with a process that is base catalysed with methanol and sodium hydroxide. The intensity in terms of parameters in transesterification was established at optimistic intensities as reported in literature, with a ratio in terms of moles as 1:8 having been reported, catalyst as having a concentration of less than 0.6 wt. % NaOH, at 50°C as a temperature condition as well as reaction time as 180 minutes. In another beaker 100 mL methanol solution was taken with 1.2 g sodium hydroxide pellets mixed into it, mixed at 450 rpm for 20 minutes. As noted above, 40 mL sodium methoxide solution was mixed with 120 mL algal oil in a way that methanol and algal bio-oil ratio in terms of moles is 1:8. The above mix as noted was transferred into a conical flask with a bottom that is flat, followed by initiation in its transesterification with heating of the flask into 50°C for a reaction time of a 180 minutes. The entire contents in the flask was poured into separating funnel and then, it was allowed for a cooling time of 180 minutes. Upon the completion of bottom and upper layer of glycerol and

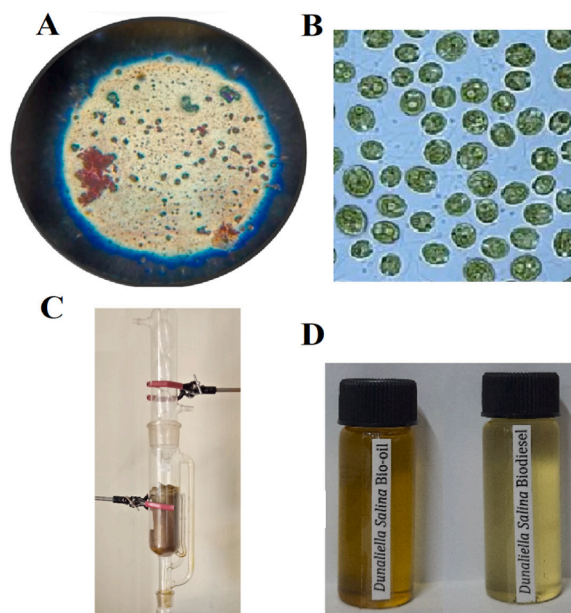


Fig. 1. *Dunaliella salina* – Microscopic view (A and B), Bio-oil extraction (C) and Extracted Biodiesel (D).

algal biodiesel in accordance with the transesterification process, ring formation difference was noticed [18,19]. The traces of water molecules were removed. Transesterification efficiency of *Dunaliella salina* was 93 %.

### 2.2. Fuel properties and standardization

Properties are tested for the fuel that is used in the diesel engine in order to meet with operational requirements is as listed in Table 1. The isolated biodiesel also experienced some spectroscopic studies like Fourier Transform Infra-Red Spectrometry, Nuclear Magnetic Resonance and Gas Chromatography Mass Spectrometry in order to study its feasibility in a CI engine as a blended fuel with pure diesel. Table 1 presents in depth the physico-chemical properties of resulting *Dunaliella salina* bio-oil as well as its biodiesel in comparison with straight diesel. The density of resulting *Dunaliella salina* bio-oil as well as its biodiesel was 864 kg/m<sup>3</sup> as well as 858 kg/m<sup>3</sup> which is 3.09 % more in comparison with straight diesel. The flash point of resulting bio-oil was lowered substantially by as much as 3.58 % from 112°C to 80°C through esterification process as well as was much closer to straight diesel. The gross calorific value increased substantially up to 39.756 MJ/kg depicting its viability as a fuel in CI engine. The kinematic viscosity also

Table 1  
Test Fuel Properties.

Properties	Diesel	<i>Dunaliella salina</i> Bio-oil	<i>Dunaliella salina</i> Biodiesel	DuSaBD20
Density (Kg/m <sup>3</sup> )	838	864	858.42	840
Flash Point (°C)	75	112	80	77
Calorific value (MJ/kg)	43.8	30.75	39.75	42.45
Viscosity (at 40°C) (mm <sup>2</sup> /s)	1.9 - 4.1	18.259	5.2	2.92
Sulphur content ( % vol)	0.038	0.21	0.10	0.041
Oxygen content ( % wt)	0	4.468	6.128	2.154
Ash content	0	1.523	0.758	0.232
Cetane number	48	37	43	47

increased substantially up to 5.2 mm<sup>2</sup>/s at 40°C in case of *Dunaliella salina* biodiesel. The transesterification process infused a significant quantity of Oxygen upto 6.128 % by weight to the *Dunaliella salina* bio-oil making it enriched towards the combustion process. All the physio-chemical evaluation was conducted in accordance with ASTM D6751 standards. The blending of DuSaBD upto 20 % by volume with straight diesel exhibited notable improvements in the test fuel properties making it more suitable to be used as a substitute fuel for CI engine.

In wide, it can be noted from the recent research that Hydrogen-enriched fuels have demonstrated remarkable improvements in engine performance, including enhanced thermal efficiency and reduced fuel consumption. Studies indicate significant reductions in exhaust emissions such as HC, CO, CO<sub>2</sub>, and NO<sub>x</sub> under optimal operating conditions in both SI and CI engines. Improved combustion characteristics, attributed to hydrogen's high calorific value and rapid flame speed, further enhance engine efficiency. These benefits are achievable with minor engine modifications like upgraded ignition systems and iridium spark plugs for SI engines. The findings highlight hydrogen's potential as a cleaner alternative fuel. Proper implementation can lead to sustainable advancements in internal combustion technology [20]. Hence in this study without modifying the engine setup the hydrogen is inducted at low flow rates to enhance the engine characteristics.

### 3. Experimental setup

Experimental experiments in Kirloskar 240PE single cylinder, water cooled, naturally aspirated, direct compression ignition, four stroke engine with hydrogen addition in intake manifold are conducted in the present work. The straight diesel fuel and DuSaBD20 are kept at a very minimal level in two fuel reservoirs and its mixing in volumetric ratio in a preheat condition is triggered before its intake into cylinder of the engine through fuel injector. A different arrangement is made in cylinder head for hydrogen gas admittance in a metered way into intake manifold as shown in Fig. 2. The technical specification in a detailed way is provided in Table 2.

Test load on the engine is obtained with a eddy current dynamometer interfaced with the dynamo controller. Kristler cylinder head pressure sensor measures in-cylinder pressure fluctuations in a real time with the assistance from Data Acquisition System (DAS). The combustion analyzer measures important data like HRR, NHR, Ignition delay, SOC, CD and mass fraction burnt in order to study combustion phenomenon. The exhaust gas temperature as well as speed of the engine have been recorded with a combination of non-contact optical sensor with a K-type thermocouple interfaced with the engine. The AVL444 gas analyzer is used in order to measure CO, HC, NOx, CO<sub>2</sub> as well as O<sub>2</sub> whereas AVL437 is used in order to measure the current investigation's smoke

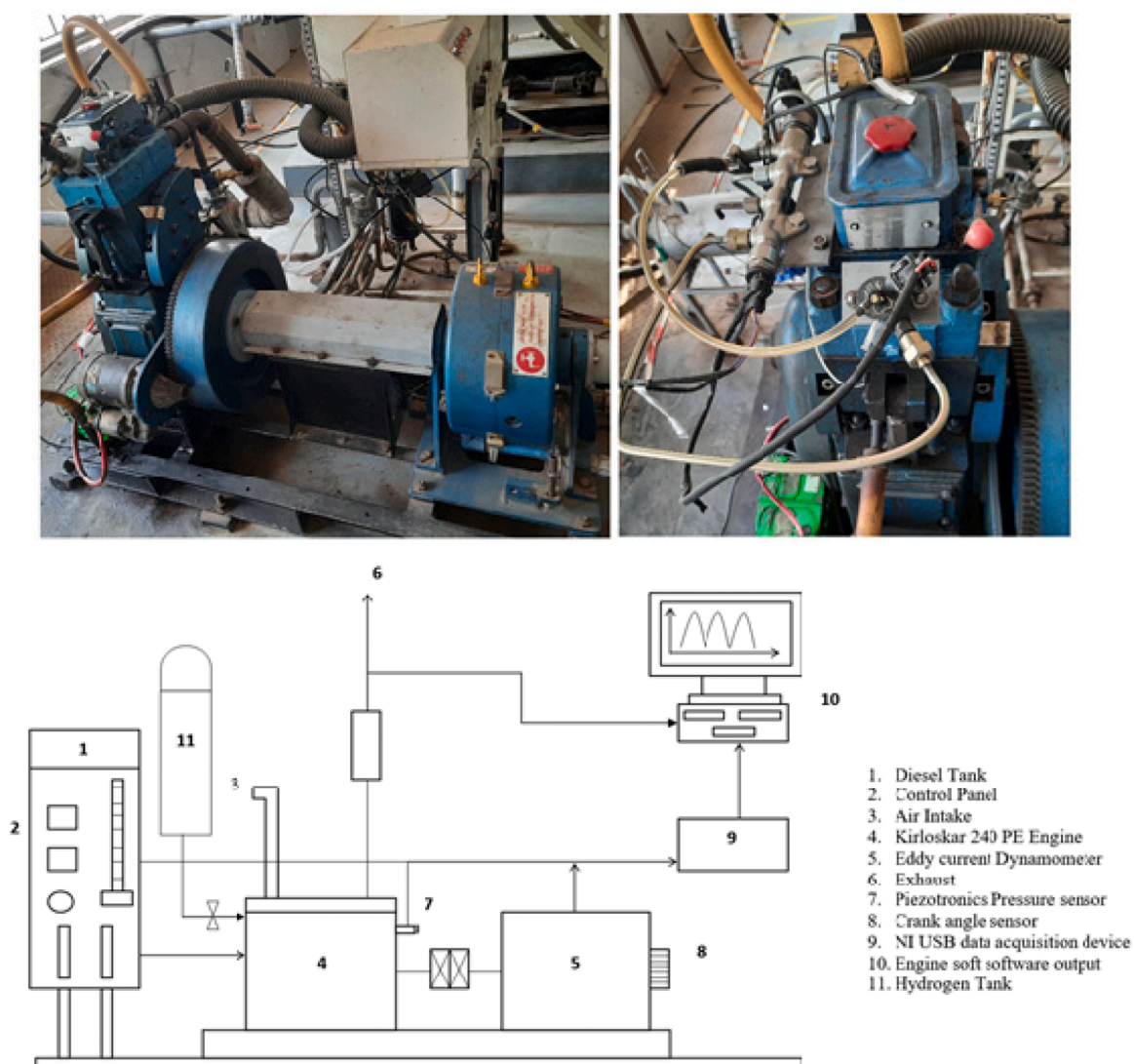


Fig. 2. Experimental test engine and Schematic.

**Table 2**  
Engine Specification.

Make	Kirloskar 240PE, water cooled, 4 stroke, DI CI engine
Bore / Stroke	87.5 / 110 mm
Cooling system	Water cooled
Fuel tank	10 liters (2 nos) with separate measuring arrangement
Loading	Eddy current dynamometer
Rated speed and power	1500 rpm and 5.2 kW
Crank angle encoder	1°CAD resolution
Calorimeter	Pipe in pipe type
Water pump	Mono block type
Injection pressure and timing	180-220 bar and 23°C bTDC
Stroke volume	661 cc
Number of cylinder	1
Number of injection nozzle	3
Diameter of the nozzle	0.3 mm
Fuel spray angle	120 degree
Compression ratio	17.5:1

opacity.

The experimental trials were conducted with straight diesel as a base fuel at all loads, followed by DuSaBD20 fuel blend at similar loading condition. A warmup time of 10 minutes on engine operation was allowed before the change of each fuel type. Further, hydrogen gas was supplemented at 2LPM, 4LPM and 6LPM with equal intervals at no load, low load, part load and full loading conditions.

#### Uncertainty Analysis

The reading taken and utilised may have vagueness such as static error, human error, and instrument error for which error calculation is required. The derived data is given in Table 3 for estimating the Uncertainty parameter for combustion and emission attributes using the following Eq. (1).

$$R = \sum (U_i^2) = 1.47\% \quad (1)$$

Where R = Root mean square value of the uncertainty  
 $U_i$  = Uncertainty values of the parameters.

## 4. Results and discussion

### 4.1. Biodiesel conversion optimization

The oil extracted from the algae *Dunaliella salina* was converted into biodiesel using base catalysed transesterification process as detailed in the previous section. The conversion process was verified by optimizing the parameters that were used in the transesterification. The parameters that had the influence in conversion were the catalyst used, methanol to oil ratio, temperature during the process and the time duration of the process. While performing the transesterification in order to optimize the conversion by the influence of these parameters the following changes were experimented. The methanol to oil ratio widely practiced

in biodiesel conversion are 1:8, 1:7 and 1:6 which was also taken into consideration for this experimental analysis, the catalyst concentration used in this study in terms of weight are 0.5 %, 1 % and 1.5 %, the temperature used for the study are 40°C, 50°C and 60°C and the time duration in terms of 1 hr, 2 hr and 3hr [21].

The various operating parameters were considered are detailed in Table 1, the methanol to oil ratio 1:8, catalyst concentration 1 % wt, temperature 50°C, time duration 3 hr and the best output response of biodiesel yield is 93.99 %. Similarly, the methanol to oil ratio 1:7, catalyst concentration 1.5 % wt, temperature 60°C, time duration 2 hr and the output response is 92.95 %. Considering the next methanol to oil ratio 1:6, catalyst concentration 1.5 % wt, temperature 50 °C, time duration 2 hr and the output response is 91.89 %.

### 4.2. Biodiesel characterization

#### Gas Chromatography - Mass Spectrometer (GCMS)

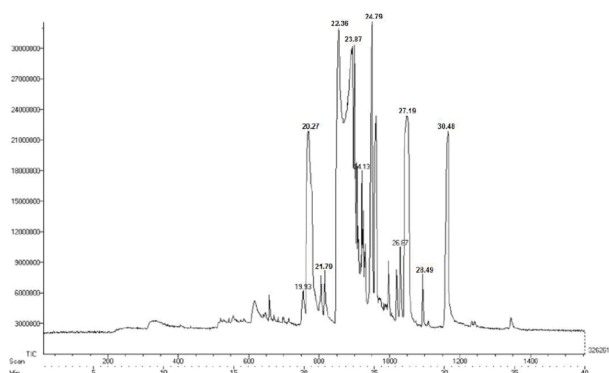
Bio-oil produced from the marine algae *Dunaliella sp.* was converted into biodiesel through a single-stage base-catalysed transesterification method with methanol and sodium hydroxide. A biodiesel sample was esterified in order to ascertain the presence of diverse FAMES and to highlight the degree of efficiency by the transesterification procedure and hence analysed by GC-MS. In the biodiesel mass chromatogram nine different FAMES were identified within RT between 19. 93 to 30. 48 minutes [22].

As a result of the analysis performed to obtain the structure of fatty acid methyl ester, different fragmentation patterns were obtained, all of which had a base peak at m/z 74. The acquired fragmentation patterns of the esterified biodiesel and mass chromatogram of the algal bio-oil demonstrated the occurrence of the McLafferty rearrangement process. Some common mass fragmentation patterns of the FAME are the carbomethoxy ion loss resulting from  $\beta$  cleavage as shown in Fig. 4. Several of the mass fragmentation patterns exhibited multiple peaks: These multiple peaks may be based on the fact that the methoxy group has been ejected out and the carbon and hydrogen atoms redistributed through the process of transesterification (Refer Fig. 3). Consequently, oleosins containing, for instance, 14,17-Octadecadienoic acid methyl ester are found at RT 22. 36 minutes due to this hydrogen ion redeployment and organization within the carbonyl group. The different fatty acid methyl ester that presented the biodiesel sample were identified as follows: RT 30.48 (tetracosanoic acid methyl ester), RT 28.49 (tricosanoic acid methyl ester), RT 27.19 (docosanoic acid methyl ester), RT 26.87 (13-docosenoic acid methyl ester), RT 24.79 (eicosanoic acid methyl ester), RT 22.36 (14, 17-octadecadienoic acid methyl ester, RT 21.79 (heptadecanoic acid methyl ester), Retention time 20. 27 (hexadecanoic acid methyl ester) and RT 19. 93 for 9-hexadecenoic acid methyl ester). The detailed fatty acid composition in *Dunaliella salina* biodiesel is given Table 4 below.

*Dunaliella salina* biodiesel details the FTIR spectra vibration between

**Table 3**  
Uncertainty Analysis.

Parameters	Uncertainty( $U_i$ )
Crank angle encoder(° CA)	0.20 %
Engine speed	0.05 %
Fuel flow rate	0.4 %
Intake air flow (l/min)	0.12 %
Load (N)	0.25 %
Measuring burette (cc)	1 %
Pressure Transducer (bar)	0.20 %
Time (s)	0.5 %
CO	0.35 %
NO <sub>x</sub>	0.33 %
Smoke opacity	0.34 %
UBHC	0.5 %

**Fig. 3.** *Dunaliella salina* Biodiesel - GCMS Chromatogram.

**Table 4**  
Fatty acid Composition in *Dunaliella salina* Biodiesel.

Retention time (RT)	Fatty acid Common name	Fatty acid systematic name	Composition (%)
19.93	Palmitoleic acid	Hexadecenoic acid methyl ester	2.155
20.27	Linoleic acid	12-Octadecenoic acid methyl ester	8.179
21.79	Lauric acid	Heptadecanoic acid methyl ester	0.456
22.36	Linolenic acid	14-17 Octadecadienoic acid methyl ester	38.146
24.79	Arachidic acid	Eicosanoic acid methyl ester	15.125
27.19	Oleic acid	Docosanoic acid methyl ester	6.451
28.49	Palmitic acid	Tricosanoic acid methyl ester	0.893
30.48	Lignoceric acid	Tetracosanoic acid methyl ester	2.456

Saturated fatty acid :24.567 %.  
Unsaturated fatty acid:72.813 %.  
Unknown components:2.62 %.

Fourier Transform Infrared Spectrometer (FTIR).

547 to 3008 $\text{cm}^{-1}$  as shown in Fig. 4. Conversion of oil to biodiesel is briefly signalled in the vibration stretch 1741  $\text{cm}^{-1}$ . A long hydrocarbon chain was noted between 1019  $\text{cm}^{-1}$  and 1460  $\text{cm}^{-1}$ , which is a group bending-stretching vibration. It was noticed that there was presence of carboxylic group at various stretches like 844  $\text{cm}^{-1}$ , 924  $\text{cm}^{-1}$ , and 1427  $\text{cm}^{-1}$ . From the FTIR spectra result it was confirmed that the complete conversion of the bio-oil and its FAMES was detailed through the strong stretches at 2863  $\text{cm}^{-1}$  and 2933  $\text{cm}^{-1}$ , whereas the weak stretch like 3018  $\text{cm}^{-1}$  also confirms the same [23,24]

Nuclear Magnetic Resonance (NMR)

*Dunaliella salina* algal biodiesel was dissolved using 0.8 ml of methanol in order to create a 1H NMR solution. The sample was injected inside the equipment with pulse 90 degrees and relaxation delay of 10 seconds. It was noted that the primary components in the biodiesel were fatty acid esters, it was also noted that there were traces of steroids, alkaloids and alkanes. It can be noted from the Fig. 5 that fatty acid ester is the peak observed at 3.669 ppm in the <sup>1</sup>H NMR spectrum of *Dunaliella salina* fuel sample. Carbonyl functional group was noted at 5.387 ppm with a strong signal. The peaks at 3.330 ppm to 2.108 ppm range shows the long unsaturated hydrocarbon chains, OCH (at 5.397 ppm) and OCH<sub>2</sub> ester groups (at 5.408 ppm) due to the conversion of triglyceride to mono-alkyl fatty acid ester. Alkenes were seen as a faint doublet peak at 3.326 ppm. Presence of polyunsaturated fatty acids in the sample was noted due to the triplet peak at 1.377 ppm. <sup>13</sup>C NMR analysis was done using deuterated methanol as a solvent, much like the sample injection proton NMR method. The peaks of triglycerides, diglycerides,

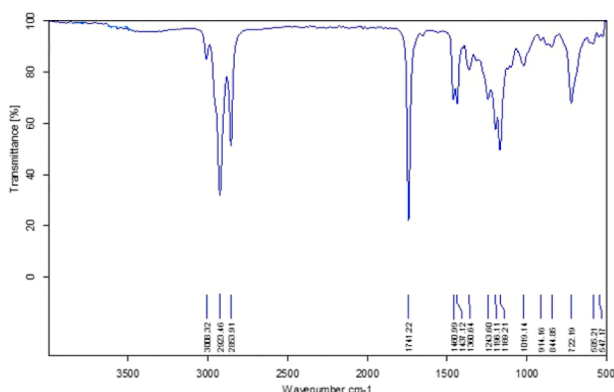


Fig. 4. *Dunaliella salina* Biodiesel – FTIR spectrum.

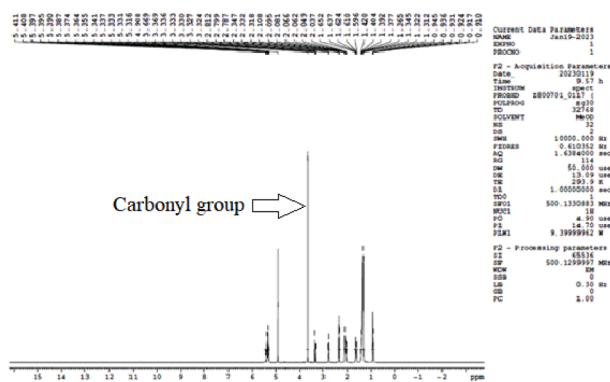


Fig. 5. *Dunaliella salina* Biodiesel – <sup>1</sup>H NMR Spectrum.

monoglycerides and epoxy ester were seen ranging between 0 ppm and 200 ppm as shown in the Fig. 6. A singlet peak was seen at 47.967 ppm, A peak ranging from 127.691 ppm to 129.567 ppm explains the presence of unsaturated esters with carbonyl groups. Transesterification occurrence was confirmed by the presence of a terminal peak at 174.417 ppm. Multiple peaks between 26.714 ppm and 33.544 ppm (represent the carboxyl group) and 16.442 ppm peak includes the existence of monoglycerides [25,26].

4.3. Combustion characteristics

In-cylinder Pressure

In-cylinder pressure is very crucial in extracting information regarding performance as well as combustion characteristics of varied fuel mixtures in a single cylinder, four-stroke diesel engine. Various mixtures of diesel-algae biodiesel-hydrogen can provide crucial information regarding combustion characteristics from a profile obtained from in-cylinder pressure. The research in question involved a comparison between 100 % diesel fuel and 20 % algae biodiesel with 80 % diesel with as well as without hydrogen flow rate variation from 2 to 6 liters a minute. In-cylinder pressure will be increased due to high energy concentration as well as auto ignition quality of diesel fuel [27]. Combustion can be seen with the sudden development of the pressure, mainly at the commencement of the power stroke and reasonably stable toward the efficiency of the energy transformation. The peak pressure of the D100 was 46.43 bar at 8 degree after the top dead center position. Algae biodiesel blend might have reduced peak in-cylinder pressure a little due to the lesser calorific value of the fuel compared to conventional diesel. The oxygen content in biodiesel may be the reason for the better combustion where the in-cylinder pressure rise was detailed as

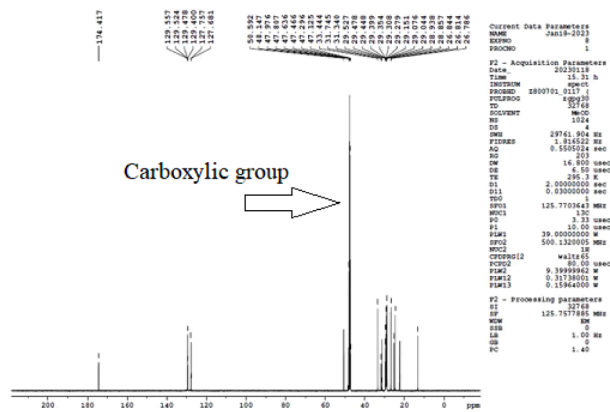


Fig. 6. *Dunaliella salina* Biodiesel – <sup>13</sup>C NMR Spectrum.

47.003 bar as shown in Fig. 7.

Hydrogen was inducted into the diesel-biodiesel blend at lower rate of 2 litres per minute (2 LPM) at which the flames accelerate, and thus pressure rise would be faster because of shortened ignition delay. High diffusivity and low ignition energy of hydrogen may be the reason behind the promotion of the homogeneity of the blend and also triggering fast combustion. However, peak pressures would remain within control with a limited volume of hydrogen introduced into the mixture as the pressure increases within the cylinder. At 8 degrees after TDC, it was observed that a pressure rise was at 47.68 bar. Whereas for 4 LPM induction into the diesel-algal biodiesel blend, the pressure was noted as 46.79 bar and for 6LPM it was noted as 47.003 bar. Hydrogen aids in combustion enhancement; it thus accelerates the pressure rise as well as the oxidation of fuel and we may say that the bio-diesel from algae is carbon neutral [28].

Rate of Pressure Rise

The rate of pressure rise is a very vital indication of the combustion characteristic in a single-cylinder four-stroke diesel engine. With the blends of diesel and algae biodiesel, 100 % diesel and 80/20 blend of diesel and algae biodiesel with varying hydrogen flow rates of 2, 4, and 6 LPM, the kinetics of combustion result in varying pressure rise rates. Diesel fuel typically has a relatively high rate of pressure rise, attributed to its high energy density and quick auto-ignition under compression. In diesel-only combustion, the pressure rise rate is primarily driven by the rapid premixed combustion phase. The rate of pressure rise value was noted as 1.62 bar/°CA at 3 degree after TDC [29]. The algae biodiesel blended with diesel has a slightly lesser rate of pressure increase than that of pure diesel. Biodiesel has a higher oxygen content and lower calorific value, giving the combustion process to be very controlled. It promoted a gentler pressure increase with the better combustion stability and it detailed 1.72 bar/°CA at 3 degree after TDC. When hydrogen was added to the diesel algal biodiesel blend at addition rate of 2 LPM the rate of pressure rise begins to increase due to its high flame speed and low ignition energy (Refer Fig. 8). Hydrogen enables the ignition of combustion sooner and more evenly, and enhanced the formation pressure rate and the ROPR was recorded as 1.72 bar/°CA at 2 degree after TDC, whereas for 4 LPM it was accounted for 1.62 bar/°CA at 3 degree after TDC and in 6LPM it was noted as 1.72 bar/°CA at 2 degree after TDC [30].

Net Heat Release Rate

The HRR in a single-cylinder engine is an indicator of energy emitted during combustion and plays a critical role in the efficiency, performance, and emissions of the engine. Many fuel combinations 100 % diesel, an 80 % diesel and 20 % algae biodiesel blend, and the latter with varying hydrogen flow rates of 2, 4, and 6 LPM-many ignition properties, flame speeds, and combustion efficiency-result in variability in HRR. Peak HRR for diesel fuel is typically very high as a result of a high energy density and well-defined premixed combustion phase. Once ignited, diesel quickly releases energy and makes the HRR profile rather

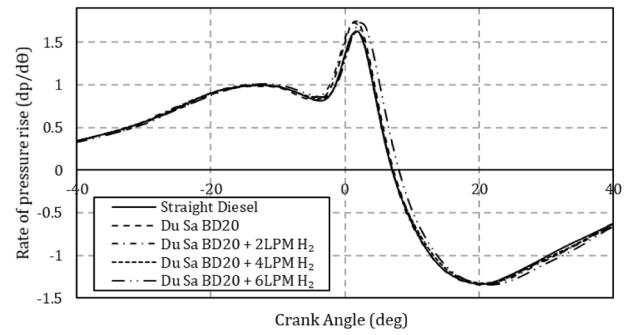


Fig. 8. Variation in Rate of Pressure rise.

sharp. The thermal efficiency and heat release of diesel combustion are often higher. The rapidity in quick release is an attribute of traditional diesel combustion, with most of the heat released during the premixed phase. D100 detailed 19.94 J/°CA at 1 degree after TDC. Biodiesel made from algae blended with diesel generally helps the combustion process by providing supplemental oxygen for thorough combustion, leading to a gentler heat release profile. Combustion was very smooth with a gradual rate of HRR, ensuring complete combustion. The heat release was found to be 20.89 J/°CA at 1 degree after TDC (Fig. 9).

Hydrogen at 2 LPM significantly elevates HRR compared to diesel fuel, attributed to low ignition energy and high flame speed of hydrogen, which enhance quicker combustion onset. The HRR increased earlier in the combustion cycle with a higher initial heat release phase compared with diesel alone. Hydrogen, as an accelerator, increases combustion efficiency and thermal output, with higher complete combustion and peak HRR at slightly elevated levels. At this hydrogen concentration the HRR was stayed within manageable limits without developing any major pressure peaks and was recorded as 20.47 J/°CA, that for 4 LPM was recorded as 19.83 J/°CA and 6 LPM as 20.47 J/°CA at 1 degree after TDC. For different blends of fuels, HRR shows that even though the addition of algae biodiesel to diesel provides a consistent base level with a subtly peak HRR, the addition of hydrogen strongly amplifies combustion by altering the HRR [7,31].

Cumulative Heat Release Rate

Cumulative heat release rate in a four-stroke diesel single-cylinder. The total energy that is released during an entire cycle of combustion; this is an essential indicator of completeness of combustion and energy use for a given fuel mix. The CHRR for pure diesel fuel is usually at a high value since its calorific value is high and energy release during combustion is efficient. This combustion of diesel is characterized by a rapid increase in cumulative heat release, especially the premixed burn phase, with a diffusion-burn phase moving at a slower rate. Baseline comparison of other fuel blends with that of the diesel CHRR can be made. Blends of 20 % algae biodiesel in diesel fuel typically contain a small increase in CHRR compared with diesel due to the lesser energy density

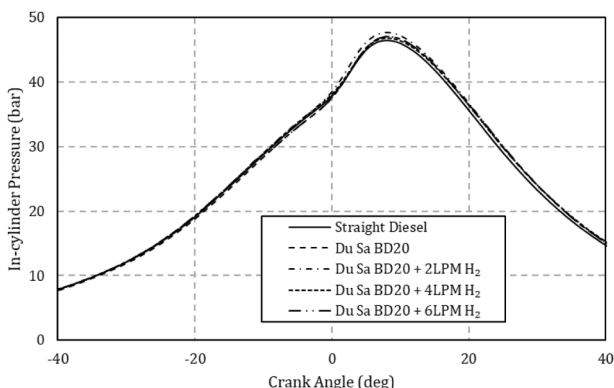


Fig. 7. Variation in In-cylinder pressure.

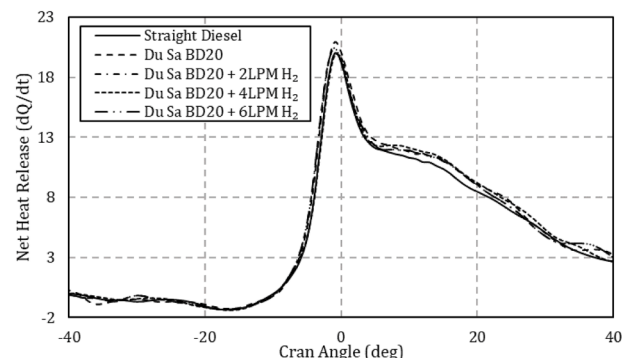


Fig. 9. Variation in Net Heat Release.

of biodiesel. However, the inherent oxygen in biodiesel assures complete combustion and partly negates this decrease. Accumulation of CHRR is more gradual in this blend as compared with 100 % diesel; thus, its energy release over the cycle is only slightly rougher. This benefit is complemented by the addition of 2 LPM hydrogen on the CHRR curve, which indicates steeper early increases in the combustion cycle, all of which arise from the contribution of hydrogen to accelerate ignition and make complete fuel oxidation more probable. This translates into improved cumulative energy release due to reduced incompleteness in combustion, resulting in a higher CHRR than the pure diesel-biodiesel blend. The added hydrogen allows a greater share of energy to be converted in a shorter combustion time. As the combustion is accomplished in a shorter time, extreme temperature spikes are avoided, and the overall combustion efficiency improves. Similar gain was also observed in 4LPM and 6LPM. A high CHRR at this level of hydrogen requires very sensitive calibration of engine parameters so as not to cause interrupted combustion and mechanically detrimental peak pressure and temperature conditions (Fig. 10).

Mean Gas Temperature

The average gas temperature of a single cylinder, CI engine is one of the important parameters since it shows combustion quality and affects emissions, as well as thermal stresses in various engine components. Different fuel blends affect MGT because of differences in combustion properties and heat release dynamics. In the case of D100, the MGT is most likely to be relatively high since diesel has high energy density, and this also has good combustion quality. High peak temperatures associated with diesel combustion are common, since the premixed phase of combustion typically releases energy fairly quickly. MGTs higher than those values would be hoped for to provide good thermal efficiency but result in an increase in NOx emissions due to the formation of hot spots within the cylinder. Diesel-only combustion typically produces stable MGTs that can be used as a platform from which to compare other fuel ratios. Adding 20 % algae biodiesel to diesel typically brings about a slightly varied MGT since the oxygen content in the biodiesel encourages full combustion with less unburned carbon, but with a slightly reduced peak temperature.

The MGT of a single-cylinder, four-stroke diesel engine is a critical parameter that speaks to the combustion efficiency as well as impacts on emissions and thermal stresses of engine components. The influence of various combinations of fuels on MGT is different in each due to the influence of combustion properties as well as the dynamics of heat release. For D100 fuel, MGT is relatively high since diesel is highly energetic and burns very cleanly (Fig. 11). Due to rapid energy release during the premixed combustion phase, diesel combustion often results in attaining high peak temperatures. High MGTs are advantageous toward strong thermal efficiency but tend to provide elevated NOx emissions due to the existence of high temperature regions inside the cylinder. Diesel-only combustion produces relatively stable MGT levels, providing a reference point for comparison of other fuel combinations.

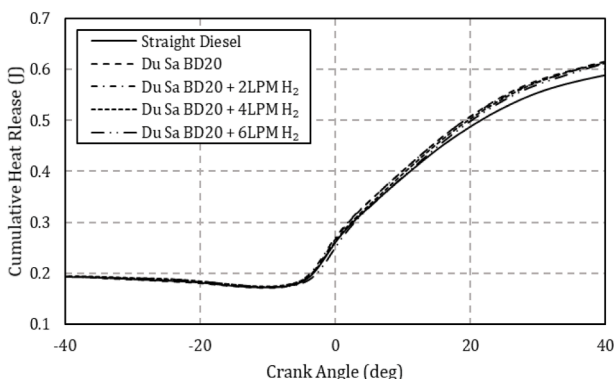


Fig. 10. Variation in Cumulative Heat Release.

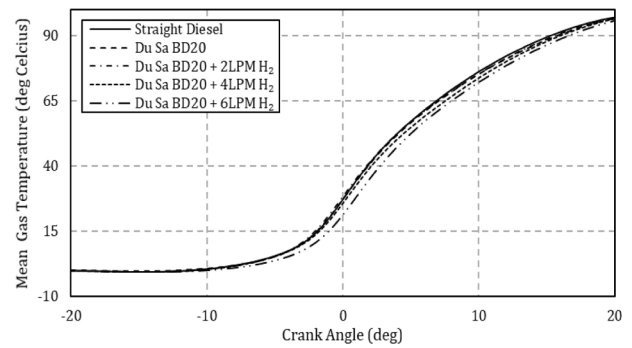


Fig. 11. Variation in Mean Gat Temperature.

Generally, 20 % algae biodiesel blended with diesel results in a slightly different MGT, because of the oxygen in biodiesel, which allows a more complete combustion with less unburned carbon but at a slightly lower peak temperature.

4.4. Emission characteristics

Unburned Hydrocarbon

UBHC emissions in a single cylinder, diesel engine helps in understanding the combustion completeness and efficiency in fuel oxidation. Analysis of UBHC emissions for different types of fuel such as Straight Diesel, diesel and algae biodiesel and this blend at different hydrogen flow rates of 2, 4 and 6 LPM would be helpful to view their combinations in terms of reduction of emissions (Fig. 12). Diesel fuel is a long carbon chain and has a complex combustion process, so it usually produces a relatively high level of UBHC emissions. UBHC emissions occur because of incomplete combustion, which happens in the low temperature or rich-mix regions of the cylinder. Overall, diesel's high energy density and fast auto-ignition characteristics favour efficient combustion, but UBHC emissions can still occur because of fuel quenching near the cylinder walls and in crevice regions.

Diesel itself can serve as a reference point when drawing comparisons of the amount of UBHC with that in other fuel blends. Usually, adding 20 percent biodiesel from algae in diesel fuel will cause reduced UBHC emissions. Biodiesel contains oxygen in it which helps in its burning up efficiently because of this oxygen that aids in the oxidation process thereby less UBHC in emitted. When diesel mixes up with biodiesel of the algae, combustion goes easy with relatively fewer rich mix regions, hence UBHC in being emitted is reduced. More importantly, the lower ignition delay of biodiesel leads to lesser UBHC emissions with

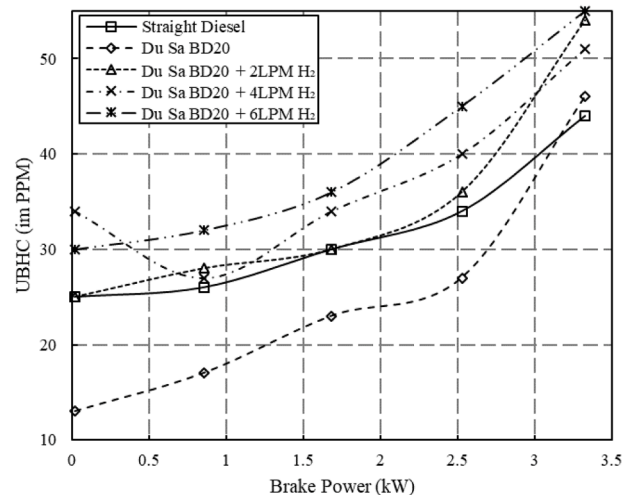


Fig. 12. Variation in UBHC.

fuel burns that are faster and closer to complete. Fuel characteristics: D100 fuel presented with stated UBHC emission at 44 ppm and in D80B20 resulted in 46 ppm.

The addition of 2 LPM of hydrogen to the diesel-biodiesel blend further variates the emissions of UBHC. Hydrogen possesses high flame speed characteristics and low ignition energy, which enhance combustion by ensuring the minimum areas of incomplete combustion with low UBHC formation. The presence of hydrogen ensures faster and, therefore, more uniformly burning; consequently, a significant reduction of UBHC as very little fuel remains oxidized within the combustion chamber. The value of D80B20, D80B20+2LPM H<sub>2</sub>, D80B20+4LPM H<sub>2</sub>, and D80B20+6LPM H<sub>2</sub> fuel was 54, 51, and 55 ppm, respectively. At this hydrogen level, UBHC emissions are almost entirely mitigated, but optimized injection timing and mixture control are essential to prevent unwanted side effects, such as knock or thermal stress. It can also be noted from the UBHC emission that the wet-stacking is negligible due to the presence of hydrogen which enhances complete combustion avoiding unburned hydrocarbon and polycyclic aromatic hydrocarbon. This may be the reason for the negligible concept of wetstacking [32] in the studied diesel engine avoiding engine failure.

Carbon Monoxide

CO is a valuable indicator of the efficiency in combustion as well as the degree of fuel oxidation. Generally, CO is formed in regions where fuel combustion is incomplete, mainly caused by insufficient oxygen or poor fuel-air mixing. The three different fuels used: 100 % diesel, diesel and algae biodiesel, and the blend with different hydrogen flow rates also impact CO emissions because of differences in combustion characteristics and oxidation potential (Fig. 13). Diesel fuel generally produces a moderate level of CO emissions due to the high carbon content in its long-chain hydrocarbon molecules. Diesel combustion relies heavily on high pressures and temperatures for complete oxidation; however, regions within the combustion chamber that experience fuel-rich or low-temperature conditions can still lead to CO formation. Diesel-only combustion establishes a baseline CO emission level for comparison with alternative fuel blends. 20 % algae biodiesel addition into diesel fuel typically reduces CO emissions. Biodiesel's inherent oxygen content aids in promoting more complete combustion, as the additional oxygen reduces the likelihood of CO formation by facilitating a more complete oxidation of carbon to CO<sub>2</sub>. The smoother combustion and better fuel-air mixing associated with biodiesel help minimize fuel-rich zones, contributing to lower CO emissions compared to diesel alone. D100 details 0.11 % and 20 % algal biodiesel detailed 0.125 % CO emission.

Adding hydrogen to the diesel-biodiesel blend further exhibits low ignition energy with increased the flame speed, thereby enhances the combustion efficiency, varying CO emissions. Due to faster combustion the CO emission is little higher since it might not have had time to combust fully which details 0.25, 0.225 and 0.313 % at 2, 4 and 6 LPM

respectively

Carbon Dioxide

CO<sub>2</sub> Emissions in a single-cylinder, gives the extent of fuel oxidation and combustion efficiency. Again, unlike Carbon monoxide, CO<sub>2</sub> emission is from complete combustion wherein the carbon in the fuel is completely oxidized. Comparing the CO<sub>2</sub> emissions of types of fuel in this study pure diesel, diesel and algae biodiesel, and this mixture with increased hydrogen flow rates may give some insight into the efficiency and environmental benefits of these fuel mixtures. Diesel combustion produces fairly high amounts of CO<sub>2</sub> emissions because the fuel contains more carbon and has a higher amount of energy density. Diesel combustion tends to be one with complete oxidation, so CO<sub>2</sub> becomes a major product of combustion. However, the amount of CO<sub>2</sub> is proportional to the carbon content in the fuel, so 100 % diesel provides a comparison amount of CO<sub>2</sub> emissions that truly reflects its high carbon content. The 20 % algae biodiesel increases CO<sub>2</sub> emissions marginally from that of pure diesel due to the lower carbon content of biodiesel (Fig 14). Algae biodiesel is oxygen-rich, which helps in efficient combustion, thereby possibly improving combustion efficiency and has a moderate change in CO<sub>2</sub> emissions. At full load conditions the CO<sub>2</sub> emission was noted to be 8.85 %, 9.27 % for straight diesel and diesel-algal biodiesel blend respectively. The addition of 2 LPM hydrogen to the diesel-biodiesel blend decreases CO<sub>2</sub> emissions per unit of fuel burned. Hydrogen as a carbon-free fuel contributes its energy without contributing to CO<sub>2</sub> formation, and thus the rate of CO<sub>2</sub> emission per unit of total energy produced is decreased.

This mixture is known to result in a complete combustion because of the high reactivity of hydrogen which means it results in good oxidation and possibly reduces CO<sub>2</sub> emission more as it produces energy without adding carbon content, and in detail, the emission value was mentioned to be 8.83 %, while for 4 LPM and 6 LPM, it was noted to be 8.54 and 8.88 % respectively. Hence, the inclusion of hydrogen in diesel-biodiesel blends is promising to reduce the generation of CO<sub>2</sub> without losing efficiency in the combustion process but should be dealt with to measure NO<sub>x</sub> emissions and thermal impact at hydrogen levels.

4.5. Oxides of Nitrogen

One of the most significant environmental concerns with respect to NO<sub>x</sub> emissions from diesel engines is that NO<sub>x</sub> has known effects of air pollution and related harmful health conditions in humans. It forms mainly under high temperature combustion conditions when nitrogen and oxygen react inside the cylinder. A comparison of NO<sub>x</sub> emission is then conducted for the five different fuels-including straight diesel, diesel with algae biodiesel, and this fuelled blend but now with hydrogen additions-to illustrate how fuel composition and hydrogen

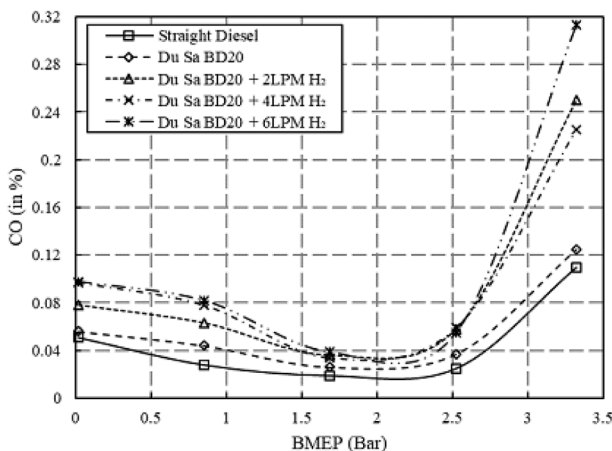


Fig. 13. Variation in CO.

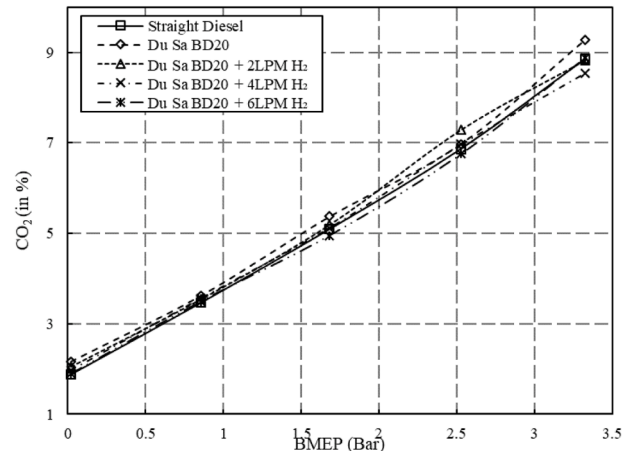


Fig. 14. Variation in CO<sub>2</sub>.

addition modify NO<sub>x</sub> levels in the engine experimented. NO<sub>x</sub> production, in general from diesel combustion tends to be high. It is a high-temperature combustion with fast energy release. This usually makes the efficient diesel engine run at temperatures above the threshold where significant NO<sub>x</sub> forms. Combustion in straight Diesel sets the baseline of NO<sub>x</sub> that can largely be attributed to the premixed combustion phase of intense heat release, which encourages the primary mechanism of thermal NO<sub>x</sub> formation. Adding 20 % algae biodiesel to diesel fuel tends to reduce NO<sub>x</sub> emissions by a few percent compared to pure diesel. Biodiesel contains oxygen, which makes combustion more complete and less sooty. Combustion temperatures are not appreciably increased, however.

The oxygen content in algae biodiesel is responsible for more complete combustion at a slightly lower temperature, which will only slightly moderate NO<sub>x</sub> emissions. However, for NO<sub>x</sub>, the effect of biodiesel is varied and is dependent upon certain combustion conditions wherein higher oxygen levels can sometimes lead to higher local temperature increases. Straight Diesel presented the value of NO<sub>x</sub> emission as 1744 ppm while diesel-algal biodiesel blend presented the value as 1762 ppm at high load. When hydrogen is added at 2 LPM, 4 LPM and 6 LPM to the diesel-biodiesel blend normally NO<sub>x</sub> emissions are increased to a small percentage (Fig. 15). The flame speed of hydrogen is higher, and the combustion tends to be faster and more complete, that may raise peak temperatures, and the increase in peak temperature increases the formation of NO<sub>x</sub> because hydrogen-enriched combustion tends to favour thermal NO<sub>x</sub> formation, and it was observed to be 1765, 1795, and 1690 ppm respectively [25].

Smoke

Incomplete combustion is the main source of the smoke emissions, wherein fuel does not completely form particulate matter due to incomplete oxidation. The study consists of values for smoke emissions for various types of fuels: 100 % diesel, and diesel with algae biodiesel for different flow rates for hydrogen addition, revealing how the composition of the fuel and hydrogen impacts on smoke (Fig. 16). Diesel fuel tends to produce relatively high smoke emissions owing to its complex hydrocarbon structure, high aromatic content, and tendency to form soot in fuel-rich regions. In diesel-only combustion, particularly with heavy loads, there is a likelihood of local fuel-rich pockets due to inadequate air-fuel mixing, which gives rise to considerable smoke emissions. The carbon content in diesel fuel is also high, as is the combustion duration, which all contribute to this baseline level of smoke emissions. Algae biodiesel added to diesel fuel generally reduces smoke emissions. Due to the presence of oxygen, it improves combustion efficiency and therefore reduces the formation of soot through the complete oxidation of hydrocarbons. The diesel-biodiesel blend results in more significant combustion with the formation of relatively fewer

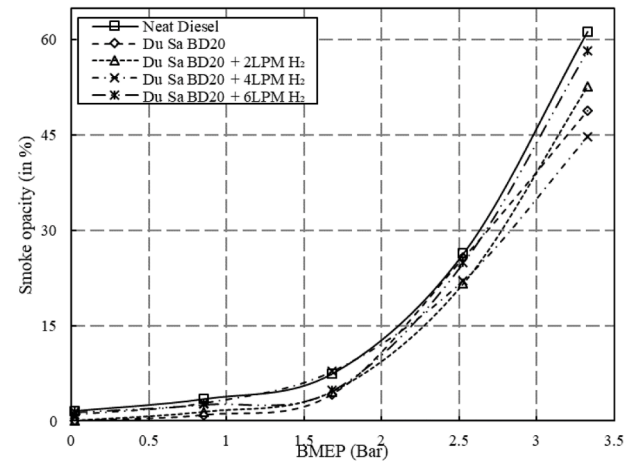


Fig. 16. Variation in Smoke.

particulates compared with pure diesel. This oxygenation effect combined with the generally lower aromatic contents of biodiesels helps decrease levels of smoke and maintain combustion efficiency. It was clear from the obtained results that straight diesel denoted 61.3 and diesel-algal biodiesel blend detailed the value as 48.9 %. Inclusion of hydrogen in the blend of diesel-biodiesel further reduces smoke emission. Hydrogen has a high diffusivity along with clean-burning properties; it does not form soot because hydrogen contains no carbon and does not participate directly in particulate formation.

The hydrogen addition improves the homogeneity of the air-fuel mixture with a fuller burn, which actually reduces smoke formation. Smoke emissions are significantly reduced at this level compared to the baseline diesel-biodiesel blend. The value for 2 LPM, 4 LPM and 6 LPM were represented as 52.6 %, 44.7 % and 58.2 % respectively. The highest smoke reduction is observed with the higher hydrogen flow rates, primarily at 4 and 6 LPM, due to the non-sooting nature and the homogeneous combustion environment that hydrogen facilitates. Diesel-biodiesel-hydrogen blends therefore have good response for the achievement of high levels of smoke reduction in diesel engines, except that additional control strategies might be required at the higher hydrogen levels to mitigate NO<sub>x</sub> emission.

The overall scenario of the Combustion and emission outcomes when the CI engine fuelled with Diesel and Blends of *Dunaliella salina* biodiesel along with Hydrogen supplementation is outlined in the Table 5 below.

4.6. Cost analysis

The cost analysis has been conducted in two ways, primarily on deriving the alga biodiesel and secondly on the engine operating efficacy. The various materials involved in the producing the *Dunaliella salina* biodiesel are f/2 nutrient solution, cultivation chamber, algal stain, nitrogen and carbon-di-oxide gas in a controlled illuminated environment. After the growth phase, the harvested algal biomass was subjected to ultrasonic bio-oil extraction process were 650 ml of *Dunaliella salina* bio-oil was extracted. NaOH and methanol solvents were used in esterifying the derived bio-oil which was later recovered and subjected to repetitive trials. Cohesively, 125/100 ml of production cost was incurred to derive the *Dunaliella salina* biodiesel. Secondly, the operation cost was evaluated using the Brake Specific Fuel Consumption (BSFC) of the test engine and operational time duration as shown in Eq. (2)

$$C_p = BSFC \times t_p \times \rho_f \tag{2}$$

Where C<sub>p</sub> is the operational cost, t<sub>p</sub> is the operation time duration and ρ<sub>f</sub> is the total fuel cost

Considering, the diesel fuel, *Dunaliella salina* biodiesel blends along

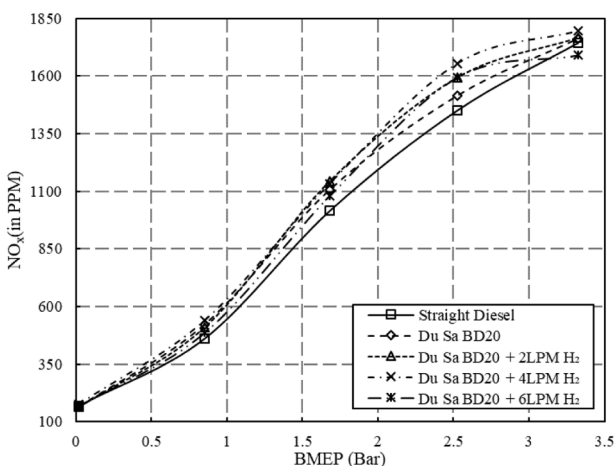


Fig. 15. Variation in NO<sub>x</sub>.

**Table 5**

Engine performance – Combustion and emission – A snap-shot.

Fuel blends	Combustion parameters		Emission parameters					
	In-cylinder pressure (bar)	HRR (J/°CAD)	CHR (J)	UBHC (ppm)	CO (%)	NOx (ppm)	CO2 (%)	Smoke (%)
Straight diesel	46.43	19.94	0.6139	44	0.11	1744	8.85	61.3
DuSaBD20	47.03	20.89	0.6487	46	0.125	1762	9.27	48.9
DuSaBD20+2LPM H <sub>2</sub>	47.68	20.47	0.6382	54	0.25	1765	8.83	52.6
DuSaBD20+4LPM H <sub>2</sub>	46.78	19.83	0.6412	51	0.225	1795	8.54	44.7
DuSaBD20+6LPM H <sub>2</sub>	47.01	20.39	0.6382	55	0.313	1690	8.88	58.2

with Hydrogen supplementation at 2 LPM, 4 LPM and 6 LPM from the established period of 12 months, the operational cost was found to be escalated marginally during the no load and low load operation during which larger quantity of fuel was consumed which then reduced considerably on 3/4th load and full load operations. The maximum cost incurred was ₹6589/kWhr, ₹6672/kWhr, ₹7071/kWhr, ₹7189/kWhr and ₹7103/kWhr for Straight diesel, DuSaBD20, DuSaBD20+H<sub>2</sub>2LPM, DuSaBD20+H<sub>2</sub>4LPM, DuSaBD20+H<sub>2</sub>6LPM test fuel respectively.

On an overview, blending DuSaBD upto 20 % by volume with straight diesel increased the fuel cost by 3.42 %, whereas the supplementing H<sub>2</sub> at 2LPM, 4LPM and 6LPM with diesel-biodiesel blends marginally reduced the total fuel cost by upto 1.433 % on comparing with straight diesel and DuSaBD20 test fuel.

## 5. Conclusion

This study demonstrated the potential of *Dunaliella salina* microalgae as a sustainable feedstock for biodiesel production, achieving a conversion efficiency of 93.99 % through an optimized single-stage transesterification process. Advanced analytical techniques, including FTIR and NMR, confirmed the successful conversion of bio-oil into fatty acid methyl esters (FAME). The comparative combustion and emission analysis of diesel, algae biodiesel, and hydrogen-enriched blends in a single-cylinder diesel engine provided valuable insights into their performance.

The results revealed that while diesel fuel exhibited the highest in-cylinder pressure and rapid combustion due to its high energy density, it also generated substantial NOx emissions. Algae biodiesel improved combustion stability and significantly reduced emissions of unburned hydrocarbons (UBHC), carbon monoxide (CO), and smoke, though NOx emissions saw a modest increase. The introduction of hydrogen further enhanced combustion characteristics, increasing the rate of pressure rise and heat release while minimizing smoke emissions due to more complete combustion. However, the rise in combustion temperatures led to a slight increase in NOx emissions.

Overall, the diesel-algae biodiesel-hydrogen blends offer a promising solution for improving combustion efficiency and reducing harmful emissions, particularly CO and smoke, making them a viable alternative for greener diesel engine operation. The slight increase in NOx emissions with hydrogen addition can be addressed through further optimization of hydrogen flow rates and the integration of after-treatment technologies.

The hybrid biodiesel-hydrogen fuel blend is more fuel flexible, improving energy security in comparison with pure hydrogen and pure biodiesel. The blend is more fuel-efficient in burning, emitting lower levels of CO, HC, and particulate matter than pure biodiesel. The blend, however, emits more NOx due to enhanced burning temperature. The requirements for hydrogen storage and infrastructure make it complex and costly. Engine adjustments may be necessary if we consider higher flow rates, which makes it difficult to deploy.

The main results in this study may be attributed as *High Biodiesel Yield*: Microalgae *Dunaliella salina* achieved 94 % bio-oil extraction efficiency and 93.99 % biodiesel conversion via a base-catalyzed transesterification process. This renders it an attractive high-yield, sustainable biofuel source. *Emission Reductions*: Algae biodiesel reduced

CO, UBHC, and smoke emissions, rendering it a cleaner fuel compared to diesel. Nevertheless, there was a slight increase in NOx emissions because of increased combustion temperatures. *Combustion Characteristics*: In-cylinder pressure was greater and combustion was faster in the case of diesel, while algae biodiesel enhanced combustion quality and decreased emissions. The addition of hydrogen improved efficiency and reduced smoke emissions but increased NOx marginally.

It can be noted that few recommendations shall be taken up as the gap to be worked towards this concept such as Optimization of NOx Emissions Control, Large-Scale Cultivation and Feasibility in Commerce, Long-Term Engine Performance and Wear Analysis, Fuel Blend Optimization and Stability Investigations, Integration with Renewable Energy Systems.

This study underscores the potential of biodiesel-hydrogen blends as a cleaner, more sustainable option for transportation, paving the way for future innovations in fuel and combustion systems.

## CRedit authorship contribution statement

**Hariram V**: Formal analysis, Data curation, Conceptualization. **Sathishbabu R**: Software, Resources, Project administration. **Godwin John J**: Software, Methodology, Investigation. **Nandagopal Kai-liappan**: Writing – review & editing, Resources, Data curation. **Vijayakumar K**: Resources, Project administration, Methodology. **Sangeeth Kumar E**: Software, Resources, Project administration. **Kamakshi Priya K**: Validation, Supervision, Software.

## 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.

## Funding

Not applicable.

## Data availability

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

## References

- [1] M.A. Jackson, F.J. Eller, Isolation of long-chain aliphatic alcohols from beeswax using lipase-catalyzed methanolysis in supercritical carbon dioxide, *J. Supercrit. Fluids* 37 (2) (2006) 173–177, 1.
- [2] R. Naureen, M. Tariq, I. Yusoff, A.J. Chowdhury, M.A. Ashraf, Synthesis, spectroscopic and chromatographic studies of sunflower oil biodiesel using optimized base catalyzed methanolysis, *Saudi J. Biol. Sci.* 22 (3) (2015) 332–339, 1.
- [3] A.S. Ramadhas, S. Jayaraj, C. Muraleedharan, Theoretical modeling and experimental studies on biodiesel-fueled engine, *Renewable Energy* 31 (11) (2006) 1813–1826, 1.
- [4] M. Sui, Z. Zhu, F. Li, H. Wang, C. Tang, Effect of oxidation on the combustion flame characteristics of *Jatropha* biodiesel, *Fuel Process. Technol.* 252 (15) (2023) 107972.
- [5] Y. Chen, J. Zhang, Z. Zhang, W. Zhong, Z. Zhao, J. Hu, Utilization of renewable biodiesel blends with different proportions for the improvements of performance and emission characteristics of a diesel engine, *Heliyon* 9 (9) (2023), 1.

- [6] M. Santasnachok, C. Chinwanicharoen, W. Ruengphrathuengsuka, E. Sutheerasak, Diesel-engine generator tests fueled with ethyl and methyl esters of palm oil as catalyzed by potassium hydroxide, *Energy Rep.* 9 (1) (2023) 48–55.
- [7] H. Venkatesan, S. Sivamani, T M Premkumar, P. Tharun, Reduction of exhaust emissions using a nanometallic enriched lemongrass biodiesel blend, *Energy Sources Part A* 39 (21) (2017) 2065–2071, 2.
- [8] J.G. John, V. Hariram, B. Gajalakshmi, J.A. Jeffrey, C.B. John, Emission characteristics of third grade oil converted sesame biodiesel, *Int. J. Vehicle Struct. Syst.* 13 (3) (2021).
- [9] J. Godwin, V. Hariram, S. Seralathan, R. Jaganathan, Effect of oxygenate on emission and performance parameters of a CI engine fuelled with blends of diesel-algal biodiesel, *Int. J. Renew. Energy Res.* 7 (4) (2017) 2041–2047.
- [10] M. Anish, J. Jayaprabakar, P. Bency, N. Joy, V. Jayaprakash, K. Arunkumar, J. Aravind Kumar, T.R. Praveenkumar, A.A. Ghfar, M. Rajasimman, B. Ravindran, Impact of reactivity controlled compression ignition (RCCI) mode engine operation in diesel engine powered with B20 blend of waste cooking oil biodiesel, *Sci. Rep.* 13 (1) (2023) 4798, 23.
- [11] K. Ramalingam, M. Kandasamy, G. Subbiah, S. Vellaiyan, Y. Devarajan, D. Chandran, R. Raviadaran, Energy, environmental, and economic benefits of Hydrogen-Enriched biofuel using ammonium hydroxide in reactivity-controlled compression ignition engines, *Results Eng.* 24 (2024) 103672, <https://doi.org/10.1016/j.rineng.2024.103672>.
- [12] R. Jayabal, Environmental and energy impacts of lychee seed biodiesel blends with acetylene fumigation in a dual-fuel diesel engine, *Results Eng.* (2024) 103659.
- [13] V. Hariram, A. Saravanan, V. Nadanakumar, M. Vinoth Kumar, M. Balachandar, J. G. John, S. Seralathan, K.L. Vasudev, Optimized grapeseed biodiesel production and its effect on the ci engines combustion characteristics at variable compression ratios, *IJVSS* 14 (2) (2022), 1.
- [14] W. Zhong, F. Yan, J. Wang, W. Gao, G. Xu, Z. He, L. Hua, Q. Wang, Experimental study on combustion and emission characteristics of fatty acid methyl esters and hydrogenated catalytic biodiesel/diesel blends under world harmonized steady state cycle, *Fuel* 343 (1) (2023) 127887.
- [15] N. Yilmaz, B. Donaldson, Combined effects of engine characteristics and fuel aromatic content on polycyclic aromatic hydrocarbons and toxicity, *Energy Sources Part A* 44 (4) (2022) 9156–9171.
- [16] C. Tsanaktisidis, A. Sormas, K. Spinthiropoulos, G. Tzilantonis, V. Vasilidis, I. Smaragdis, Variation of the physicochemical properties diesel-biodiesel blends–range 0–100%, *Pet. Sci. Technol.* 36 (11) (2018) 772–780, 3.
- [17] Q. Hu, Industrial production of microalgal cell mass and secondary products-major industrial species, in: *Handbook of microalgal culture: Biotechnology and applied phycology*, 264, Blackwell Publishing Ltd, United States, 2004.
- [18] S.K. Nayak, D.B. Munuswamy, G. Subbiah, M. Naresh, Y. Devarajan, Influence of diglyme and cumene additives upon emission and combustion behaviour of diverse biodiesel fuelled diesel engine, *Res. Eng.* 25 (2025) 104255, <https://doi.org/10.1016/j.rineng.2025.104255>.
- [19] B. Saravanan, B. Musthafa, M.A. Asokan, Assessment of CI engine vibration at various injection timing and injection pressure with Ceiba pentandra biodiesel, *Int. J. Green Energy* 21 (4) (2024) 719–731, 15.
- [20] B. Chidambaranathan, G. Soundararajan, A.K. Rajendran, A. Sakthivel, Y. Devarajan, Effect of geometric profile linearisation of wind turbine blades in low wind regions, *Int. J. Interact. Des. Manuf. (IJIDeM)* (2025), <https://doi.org/10.1007/s12008-024-02221-2>.
- [21] H. Tang, S.O. Salley, K.S. Ng, Fuel properties and precipitate formation at low temperature in soy-, cottonseed-, and poultry fat-based biodiesel blends, *Fuel* 87 (13-14) (2008) 3006–3017, 1.
- [22] S. Rajkumar, J. Thangaraja, Effect of biodiesel, biodiesel binary blends, hydrogenated biodiesel and injection parameters on NOx and soot emissions in a turbocharged diesel engine, *Fuel* 15 (240) (2019) 101–118.
- [23] D. Balasubramanian, A. Rajarajan, I.P. Venugopal, C. Dineshkumar, R. Ravikumar, D.T. Le, D.N. Cao, J.F. Josephin, A. Chinnathambi, A. Pugazhendhi, E.G. Varuvel, Engine behavior analysis on a conventional diesel engine combustion mode powered by low viscous cedarwood oil/waste cooking oil biodiesel/diesel fuel mixture—An experimental study, *Process. Saf. Environ. Prot.* 184 (1) (2024) 560–578.
- [24] S. Pattanaik, A.S. Savant, H. Srivastava, A.K. Jeevanantham, P. Ramakrishnan, N. Kasianantham, D. Sakthivadivel, A. Alaswad, T. Awotwee, Combined mixture process design approach for flexible fuel maps development of ternary blends operated gasoline engine, *Process. Saf. Environ. Prot.* 180 (1) (2023) 1104–1117.
- [25] J. Jayaraman, K. Alagu, P. Appavu, N. Joy, A. Mariadhas, Impact of methyl, ethyl, and butyl ester blends of freshwater algae oil on the combustion, performance, and emissions of a CI engine, *Energy Fuels* 34 (8) (2020) 9763–9770, 8.
- [26] J. Yano, T. Aoki, K. Nakamura, K. Yamada, S.I. Sakai, Life cycle assessment of hydrogenated biodiesel production from waste cooking oil using the catalytic cracking and hydrogenation method, *Waste Manage.* 38 (1) (2015) 409–423.
- [27] B.S. Souza, D.M. Pinho, E.C. Leopoldino, P.A. Suarez, F. Nome, Selective partial biodiesel hydrogenation using highly active supported palladium nanoparticles in imidazolium-based ionic liquid, *Appl Catal.* A 433 (8) (2012) 109–114.
- [28] C. Hu, D. Creaser, S. Siahrostami, H. Grönbeck, H. Ojagh, M. Skoglundh, Catalytic hydrogenation of C [double bond, length as m-dash] C and C [double bond, length as m-dash] O in unsaturated fatty acid methyl esters, *Catal. Sci. Technol.* 4 (8) (2014) 2427–2444.
- [29] G. Kongprawes, D. Wongsawaeng, K. Ngaosuwan, W. Kiatkittipong, S. Assabumrungrat, Low-temperature and atmospheric pressure plasma for palm biodiesel hydrogenation, *Sci. Rep.* 11 (1) (2021) 14224, 9.
- [30] G. John, V. Hariram, S. Seralathan, Emission reduction using improved fuel properties of algal oil biodiesel and its blends, *Energy Sources Part A* 40 (1) (2018) 45–53, 2.
- [31] V. Hariram, S. Vasanthaseelan, Optimization of Base catalysed Transesterification and Characterization of Brassica napus (Canola seed) for the production of Biodiesel, *Int. J. ChemTech Res.* 8 (9) (2015) 418–423.
- [32] C. Thiagarajan, Y. Devarajan, The urgent challenge of ocean pollution: impacts on marine biodiversity and human health, *Reg. Stud. Mar. Sci.* 81 (2025) 103995, <https://doi.org/10.1016/j.rsma.2024.103995>.