Performance and exhaust emission characteristics investigation of compression ignition engine fuelled with microalgae biodiesel and its diesel blends

Bhojraj Kale1,2 · Sewan Das Patle1 · Vijay Khawale3 · Sandeep Lutade2

Received: 30 August 2021 / Accepted: 13 November 2021 / Published online: 30 November 2021
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Abstract
Biofuels extracted from plant biomass can be used as fuel in CI engines to lower a hazardous atmospheric pollutant and mitigate climate risks. Furthermore, its implementation is hampered by inevitable obstacles such as feedstocks and the crop area required for their cultivation, leading to a lack of agricultural land for the expansion of food yields. Despite this, microalgae have been discovered to be the most competent and unwavering source of biodiesel due to their distinguishing characteristics of being non-eatable and requiring no cropland for cultivation. The objectives of this paper was to look into the potential of a novel, formerly underappreciated biodiesel from microalgae species which could be used as a fuel substitute. Transesterification is being used to extract the biodiesel. Microalgae are blended with petroleum diesel in percentage to create microalgae blends (MAB) as needed for experimentation. The impact of biodiesel on performance as well as exhaust emission attributes of a 1-cylinder diesel engine was experimentally studied. Compared to petroleum diesel, different blend of microalgae biodiesel showed a decline in torque and hence brake power, resulting in an average fall of 7.14 % in brake thermal efficiency and 11.54 % increase in brake-specific fuel consumption. There were wide differences in exhaust emission characteristics, including carbon monoxide and hydrocarbon, as the blend ratio in diesel increased. Moreover, nitrogen oxides and carbon dioxides increase in all algae biodiesel blends, but they are still within the acceptable range of petroleum diesel.

Keywords Algal biodiesel · Emission characteristics · Performance characteristics · VCR CI engine

Nomenclature
ASTM American Society for Testing and Materials standards
BP Brake power
BSFC Brake-specific fuel consumption
BTE Brake thermal efficiency
CO Carbon monoxide
CO₂ Carbon dioxide
FAME Fatty acid methyl esters
HC Hydrocarbons
MAB10 Biodiesel blends (10 % algæ + 90% petro-diesel)
MAB20 Biodiesel blends (20 % algæ + 80% petro-diesel)
MAB30 Biodiesel blends (30 % algæ + 70% petro-diesel)
MAB40 Biodiesel blends (40 % algæ + 60% petro-diesel)
MAB50 Biodiesel blends (50 % algæ + 50% petro-diesel)
NOx Nitrogen oxides
HRR Heat release rate
CP Cylinder pressure

Responsible Editor: Philippe Garrigues

✉ Bhojraj Kale
bkle.phd2018.me@nitrr.ac.in
1 Department of Mechanical Engineering, National Institute of Technology, Raipur 492010, India
2 Department of Mechanical Engineering, Dr. Babasaheb Ambedkar College of Engineering and Research, Nagpur 441110, India
3 Department of Mechanical Engineering, Yeshwantrao Chavan College of Engineering and Research, Nagpur 441110, India
Introduction

The current state of nonrenewable fossil fuels seems to be inherently unpredictable, yet somehow the global economy is reliant on them. In this circumstance, the exhaustion of petroleum derivatives, coupled with an increase in cost, as well as a worrisome increase in levels of contamination, is a real catastrophe for the general public. Multiple potential biodiesel alternatives have already been identified with the acquisition of land for food crops. The oil output among thousands of different algal species. Because of this, the research community are in line to look for clean alternative fuels like alcohols, vegetable oils, and biodiesel (Chen et al. 2014; Dogan 2011; Demirbas 2008). Ethyl or methyl alcohol is considered as one of the right fuel replacement for diesel engines because it permits the complete consumption of diesel fuel due to more oxygen content which improves engine performance (Surisetty et al. 2011).

Experiments on a single-cylinder DI diesel engine were carried out by Mohankumar Subramaniam et al. (Mohankumar Subramaniam et al. 2020). Among the many blends examined, A20 reveals a closer match with diesel which leads in improved thermal efficiency and reduced HC, CO, smoke, and particle emissions. Other emissions, like NOX and CO2, were found to be slightly higher. The performance parameters and exhaust emissions of a diesel engine consuming biodiesel blends and diesel fuels were examined by Avinash Kumar et al. (Avinash Kumar et al. 2020). In comparison to B20 and diesel fuels, B50 demonstrated a drop in brake-specific fuel consumption (BSFC), an increase in exhaust gas temperature, and a decrease in brake thermal efficiency (BTE). With increasing loads, the CO2 proportion increased. In comparison to diesel, all of the mixes had reduced HCs. Upendra Rajak et al. (Rajak et al. 2021) numerically investigated combustion, performance, and emission characteristics of pure diesel and first-, second-, and third-generation feedstock’s diesel-biodiesel blend (B20) for diesel engine and validated the experimental results with numerical tool. As per their observations, B20 blend shows decrease in cylinder temperature by 8.2% for Jatropha curcas, engine knocking tendency by 13.47% for rapeseed, smoke by 63.85% for jojoba, oil, and NOX emission by 42.2% for Jatropha curcas compared to those from diesel fuel at CR17.5 with full engine load. The NOX emission of B20 blend was higher by 17.53% for jojoba, 23.0% for karanja, and 8.7% for fish oil compared to diesel fuel at CR17.5 with the full load. Again, Upendra Rajak et al. (Rajak et al. 2021) performed experimentation using ethanol-methanol-diesel-microalgae blends to investigate performance and emission characteristics of a DI diesel engine. They observed that engine brake torque of hybrid fuel (ethanol) emulsions was found to be high and exhaust gas temperature to be low compared with that of base fuel. Hybrid fuel (methanol) emulsions help to increase the cylinder pressure (CP). With the hybrid fuels blend, the ignition delay period and combustion duration of hybrid fuel blends are increased. With the addition of spirulina microalgae, the ignition delay period of spirulina microalgae-diesel blend fuel is shortened. Engine emission results indicated that spirulina microalgae emulsions fuel reduces the specific particulate matter (PM), soot and smoke emissions except nitrogen oxides (NOX) emissions, but carbon dioxide (CO2) emission to be higher compared with base fuel.

Although profound study has been carried out to investigate the CR influence on performance characteristics of a CI engine using many biodiesel blends, the case of microalgae biodiesel blends has not been extensively investigated. In cited research, the effect of CR along with greater microalgae biodiesel blend fractions, on the performance and emission characteristics of single-cylinder DI variable compression ratio (VCR) CI engines, has not been meticulously explored and examined. The intense study of the reviewed literature reflects that this area requires more investigation to explore promising conclusion. To comply with the need of unexplored features found in literature review, this work aims to investigate experimentally the effects of CR on the performance and emission characteristics of a VCR diesel engine operating with five microalgae biodiesel blends as fuel.

Materials and methods

Algae absorb carbon dioxide from the environment and replenish it with ambient oxygen using photosynthetic mechanisms. Algal biodiesel plants are set up close to energy generating units, which produce loads of carbon dioxide. Reusing carbon dioxide reduces pollution in the environment. Furthermore, algae can grow in any location, under any atmospheric circumstances, without interfering with the acquisition of land for food crops. The oil output per acre land varies from 19,000 to 57,000 liters per acre among thousands of different algal species. Because of this oil concentration, algae are a better candidate for biodiesel production (Fig. 1).
Adopting the standard procedure suggested by the American Society for Testing and Materials (ASTM), raw algae were converted into algae methyl ester (biodiesel) by means of widely used transesterification process. Transesterification reduces the viscosity of algae oil considerably and enhances the combustion properties required for complete combustion in association with inbuilt oxygen content of algae. The main ingredient in this reaction is alcohol, generally methyl or ethyl alcohol, with the catalytic agent either being NaOH (sodium hydroxide) or KOH (potassium hydroxide). This experiment’s chemicals were procured from a nearby chemical supplier. The catalyst in this experiment was KOH, while the reaction media was methyl alcohol. These two were combined for a chemical reaction with microalgae oil at 65°C for 3 to 4 h. The arrangement was designed to make sure appropriate mixing throughout the chemical reaction. This method results in two layers of algal biodiesel and glycerol. At the top is microalgae biodiesel and next is glycerol. The needed biodiesel was extracted after sifting the glycerol with a separator. As a result, the resulting biodiesel was put to the test in order to evaluate its physiochemical properties. Afterward, the blends of biodiesel were prepared on volumetric basis for experimentations. The magnetic stirrer is employed for proper mixing of algae biodiesel with diesel. After stirring, the solution is kept for 24 h to observe the proper mixing. For each test, 2 l of fuel is prepared considering spillage and other losses. The lipid components of microalgae fatty acid methyl ester (FAME) are described in Table 1.

The physiochemical properties of blends were found out to be within the acceptable limits of the ASTM. The physiochemical properties of microalgae biodiesel and its blends are presented in Table 2.

Experiments were conducted on a 1-cylinder engine setup coupled with an eddy current dynamometer (Fig. 2). The setup allows for compression ratio change ranging from 12.5:1 to 18.5. The detailed specifications of experimental test rig are summarized in Table 3. All of the experiments were carried out as per normal operating procedures.

Figure 3 shows a MARS Multi Gas Analyzer (Model: MN-05, ARAI Approved) being used to monitor emission parameters. Table 4 shows the measurement range as well as the accuracy of the Multi Gas Analyzer.

### Uncertainty assessment

Instrument selection, environmental conditions, calibration, testing, observation, and obtaining readings can all cause uncertainties and errors. Uncertainty can be induced by two aspects in any instrument: fixed errors, which can be accounted for by their repeatability, and random errors, which may be computed analytically. The uncertainty of any measured parameter (xi) was calculated using the Gaussian distribution method, as shown in Eq. (6.14), with a confidence limit of 2 in this study (95 % of measured value lie within the limits of 2 of mean).

$$\Delta X_i = \left(\frac{2\sigma_i}{X_i}\right)100$$  \hspace{1cm} (1)

where

Xi — Number of reading

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**Table 1** Microalgae FAME components

| SN | Microalgae FAME components     | Chemical formula | w/w % |
|----|--------------------------------|-----------------|-------|
| 1  | Caprylic                       | C₈H₁₆O₂         | 3.91  |
| 2  | Cis-10-pentadecanoic           | C₁₀H₂₀O₂        | 3.14  |
| 3  | Eicosapentaenoic               | C₂₀H₄₀O₂        | -     |
| 4  | Linoleic                       | C₁₈H₃₆O₂        | 12.59 |
| 5  | Linolenic                      | C₁₉H₃₀O₂        | 17.71 |
| 6  | Lauric                         | C₁₂H₂₄O₂        | 1.23  |
| 7  | Myristic                       | C₁₄H₂₈O₂        | 2.55  |
| 8  | Palmiti                        | C₁₆H₃₂O₂        | 41.24 |
| 9  | Palmitoleic                    | C₁₆H₃₀O₂        | 3.35  |
| 10 | Oleic                          | C₁₈H₃₆O₂        | 4.08  |
| 11 | Stearic                        | C₁₈H₃₆O₂        | 0.98  |
Five sets of observations for speed, load, torque, temperature, pressure, and exhaust emissions were taken during the experiment, which used commercial diesel and microalgae biodiesel blends. The computed parameters’ uncertainties were calculated using Eq. (6.15).

\[ R = f(X_1, X_2, X_3, \ldots, X_n) \]  

where \( R \) is a function of \( X_1, X_2, X_3, \ldots, X_n \).
Table 5: Uncertainties of instruments

| SN | Measuring instrument       | Range               | Accuracy | Uncertainties % |
|----|---------------------------|---------------------|----------|-----------------|
| 1  | Pressure transducer       | 0 bar to 150 bar    | ± 0.1 bar| 0.1             |
| 2  | Glass manometer           | -                   | ± 1 mm   | 1.0             |
| 3  | Speed measurement         | 0 rpm to 10,000 rpm | ± 10 rpm | 0.1             |
| 4  | Exhaust gas temperature   | 0 to 900°C          | ± 0.1    | 0.12            |
| 5  | Stop watch                | -                   | ± 0.5 s  | 0.2             |

Table 6: Uncertainties of measured parameters

| SN | Parameter measured | % of uncertainties |
|----|--------------------|---------------------|
| 1  | Brake power        | ± 0.24              |
| 2  | Brake thermal efficiency | ± 0.25             |
| 3  | Air flow rate      | ± 0.60              |
| 4  | Fuel flow rate     | ± 0.72              |
| 5  | Speed              | ± 0.10              |
| 6  | Load               | ± 0.45              |
| 7  | Nitrogen oxide     | ± 1.20              |
| 8  | Carbon monoxide    | ± 0.30              |
| 9  | Carbon dioxides    | ± 0.30              |
| 10 | Hydrocarbons       | ± 0.01              |

\[
\Delta R = \sqrt{\left(\frac{\partial R}{\partial X_1} \Delta X_1\right)^2 + \left(\frac{\partial R}{\partial X_2} \Delta X_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial X_n} \Delta X_n\right)^2}
\]

\[(3)\]

Table 5 shows the measurement instrument uncertainties. The root mean square technique was proposed by Tiegang et al. (2009) and Senatore et al. (2000) to obtain the magnitude of uncertainties and errors as given in Eq. (6.15), which is used to estimate the uncertainty in brake power, brake thermal efficiency, fuel flow, speed, and load, as shown in Table 6.

**Results and discussion**

**Performance characteristics**

Basic engine performance metrics such as BTE and BSFC were determined in this experiment for blends of microalgae biodiesel and compared with results obtained using petro-diesel fuel.

Figure 4 depicts the fluctuation in brake thermal efficiency versus engine load. As compared to petro-diesel fuel mode, brake thermal efficiency decreases with fuel blends type as the load on the engine alters plus increases as the engine load rises. The specific fuel consumption increases as the calorific value declines in the microalgae fuel blends mode, affecting the brake thermal efficiency. Additionally, when the % of blended fuel increases, the fuel’s calorific value drops, leading to decreased rate of heat release and, ultimately, a fall in the engine’s brake thermal efficiency (Kalsi and Subramania 2017). In contrast to diesel fuel, there are a 2.41 % reduction in brake thermal efficiency for MAB10 and a 7.14 % drop in brake thermal efficiency for MAB50. BTE rises as engine load rises, and previous study has found similar trends and it is hence acceptable (Elsanusi and Roy 2017; Datta and Mandal 2017; Srihari et al. 2017; Can et al. 2017; Avinash Kumar et al. 2020; Mohankumar Subramaniam et al. 2020).

BSFC is influenced directly by the test fuel’s heating value. The impact of heating value in fuel complete combustion cannot be overstated. Because biodiesel and their
blends bear a lower heating value, they have a direct impact on brake-specific fuel consumption. Figure 5 depicts the BSFC’s behavioral variability as a function of the engine’s loading. The plot clearly shows that BSFC is the lowest-cost diesel fuel, followed by all microalgae biodiesel mixes at such loads. When compared to diesel fuel, the BSFC of MAB10 enhanced by 3.43 % and MAB50 increased by 11.54 %.

Figure 5 shows that BSFC decreases with greater load for each microalgae biodiesel blend because combustion efficiency increases. The obtained results were acceptable since in a cited study (Srihari et al. 2017; Can et al. 2017; Gorji et al. 2017; Avinash Kumar et al. 2020; Mohankumar Subramaniam et al. 2020), a similar trend of result was observed.

Emission characteristics

In this experimentation for microalgae biodiesel blends and diesel fuel, engine exhaust emission characteristics such as CO$_2$, NO$_X$, HC, and CO gas emissions were determined in this experiment in accord with various loads placed on the test engine and compared to petroleum diesel fuel.

The elements that determine CO$_2$ emissions from engine exhaust include viscosity, atomization process, CR, oxygen, and engine rpm (Celik and Ozgoren 2017; Rahman et al. 2013; Gharehghani and Mirsalim 2017; Muralidharan and Vasudevan 2011; Avinash Kumar et al. 2020; Mohankumar Subramaniam et al. 2020). Figure 6 shows the variance in CO$_2$ emissions as a function of engine loading for studied fuels: petroleum diesel, MAB10, MAB20, MAB30, MAB40, and MAB50. In comparison to that of diesel, the CO$_2$ content of microalgae biodiesel blends was found to be greater. The observed values for CO$_2$ are quite compatible as compared to those for petroleum diesel, and similar observation was also observed in cited literature so these results were acceptable.

The temperature of combustion, the oxygen concentration of the fuel, and the actual space of the combustion zone were the elements that directly influence NO$_X$ emissions (Zehra and Orhan 2014). Different elements that influence NO$_X$ exhaust emissions include stoichiometry, temperature of flame, delay in ignition, fatty acid composition, heat release rate (HRR), premixing, cetane number, injection timing, as well as thermophysical properties of the fuel (Rajak and Verma 2018; Shrivastava et al. 2019; Subhaschandra and Verma 2019; Avinash Kumar et al. 2020; Mohankumar Subramaniam et al. 2020). In accordance with engine loads, Figure 7 depicts NOX exhaust emission fluctuations for microalgae biodiesel blends and petroleum diesel fuel. It has been witnessed that when the load on engine increases, so does NO$_X$ exhaust output. In comparison to petroleum diesel fuel, NO$_X$ emissions from microalgae biodiesel mixes were thought to be higher, still it is under considerable range, and same results were highlighted in cited literature.

Figure 8 shows how hydrocarbon exhaust emissions vary depending on engine load for all microalgae biodiesel blends as well as petroleum diesel. MAB10 microalgae biodiesel blends reduced HC emissions by 9.2 % compared to diesel fuel, 20.58 % compared to MAB20, 29.62 % compared to MAB30, 23.84% compared to MAB40, and 13 % compared to MAB50 microalgae biodiesel blends. Figure 8 shows
how increasing the blending % in diesel fuel affects HC emissions. This could be linked to biodiesel blends’ higher kinetic viscosity, which slows fuel atomization and hence reduces HC emissions (Çelikten et al. 2012; Avinash Kumar et al. 2020; Mohankumar Subramaniam et al. 2020).

Figure 9 depicts the changes in CO exhaust emissions for all tested microalgae biodiesel blends and petroleum diesel fuel under various engine loading levels. The CO exhaust emission is least for increasing engine loading for all the fuels evaluated, according to the observations.

Biodiesel and its blends are oxygenated fuels that allow for complete combustion which allows conversion of CO to CO$_2$ molecules, resulting in significant decline in CO emissions as compared to petro-diesel (Çelikten et al. 2012; Avinash Kumar et al. 2020; Mohankumar Subramaniam et al. 2020). The average decline in CO emission was 7.7% for MAB10, 16.8% for MAB20, 12.60% for MAB30, 13.30% for MAB40, and 14.54% for MAB50 when compared to diesel fuel. From the experimental results, it is very clear that CO emission was quite less as compared to diesel, so the microalga biodiesel and its blends can be recommended as fuel for CI engines.

The results obtained for this experimentation for performance was shown in Figures 4 and 5, and for emission, it was plotted in Figures 6, 7, 8, and 9. All these experimental results show close proximity with the outcomes of cited literature in this experimental study and already published theories which validate the proposed concept of microalgae biodiesel blend use as fuel for CI engine.

### Combustion characteristic

In this experimental investigation, two combustion characteristics were observed, mainly heat release rate and cylinder pressure. They are discussed in the following section.

The HRR versus crank angle for MAB10, MAB20, MAB30, MAB40, and MAB50, as well as diesel, is shown in Figure 10. When fuel oxidizes inside the combustion chamber, heat is produced, the gas mixture expands, and HRR rises in accordance with the increase in load. The complete combustion process of fuel is influenced by fuel characteristics. The higher the air-fuel mixing rate, the lower the fuel viscosity of fuel, leading to improved combustion quality (Paul et al. 2017). As microalgae-diesel fuel blends have a higher viscosity than base fuel, they have a shorter ignition delay and a lower HRR peak value. In comparison to that in base fuel, combustion happens earlier in microalgae-diesel fuel blends. The results reveal that as compared to base fuel, the microalgae biodiesel-diesel blends fuel has a lesser peak HRR (Paul et al. 2017; Rajak et al. 2021).
Figure 11 depicts CP versus crank angle for MAB10, MAB20, MAB30, MAB40, and MAB50 engines, as well as diesel. When fuel oxidizes inside the combustion chamber, heat is generated, the gas mixture expands, and the CP increases. It was discovered that CP increased as engine load increased. The viscosity of the fuel plays an important part in the complete combustion process as well as the injection process. It is clear that the higher the air-fuel mixing rate, the lower the fuel viscosity, resulting in enhanced combustion quality (Paul et al. 2017; Chen et al. 2020). Due to higher viscosity and density, the microalgae-diesel fuel blends were shown to have a lower CP than the baseline fuel. Lower cetane number and latent heat of evaporation that correspond to microalgae biodiesel blends were also some factors which affect the ignition delay as well as cylinder pressure (Paul et al. 2017; Chen et al. 2020; Rajak et al. 2021).

Conclusion

In this paper, the impacts of five microalgae biodiesel blends on performance as well as emission characteristics of single-cylinder, direct injection CI were investigated experimentally. To exhibit its influence, these results are compared with petroleum diesel which leads to major conclusions as:

1. The physiochemical properties of all five microalgae biodiesel blends are within standard specified by the ASTM.
2. It is observed that there is an average 7.14 % reduction in BTE as compared to petro-diesel fuel for blends of microalgae biodiesel.
3. As the load increases, the BSFC declines because for high loads, the temperature inside engine cylinder is also high and the fuel viscosity decreases with high temperature which appropriates atomization of fuel molecules. In comparison to petroleum diesel, BSFC was noted 11.54 % (in average) higher for all microalgae biodiesel blends.
4. Since microalgae biodiesel is oxygenated fuel, they possess extra oxygen which reacts with CO to form CO₂, so for every microalgae biodiesel blend, CO₂ emission increases, but it is compatible with diesel fuel.
5. As the blending ratio of microalgae increases, the H/C ratio also increases. These hydrogen and carbon radicals attack the earlier phase flame to form oxides of nitrogen, so obviously it has been found that as engine load increases, NOₓ exhaust output increases. However, by utilizing cutting-edge technology such as engine operating parameters and exhaust gas control, this problem can be successfully addressed.
6. For all microalgae biodiesel blends, the decrease in HC as well as CO emissions when compared to petro-diesel fuel. This can be correlated with the higher content of oxygen in microalgae blends which results in improved mixing rate and combustion.

According to the results of the aforementioned experiment, microalgae biodiesel blend MAB20 possesses physiochemical qualities similar to petro-diesel. It achieves the best results in terms of performance and exhaust emission characteristics. Henceforth, it can be concluded that microalgae biodiesel blends with 20 % of biodiesel and 80 % of petro-diesel blend at standard temperature gives marginally superior performance and condensed exhaust emission as compared to petroleum diesel.

The impact of microalgae biodiesel blends using nanoparticles and nanotubes on performance and emission of VCR CI engine will be conducted in the future because
as per literature reviewed, nanoparticles can reduced the NOx emissions.

Authorship contribution Bhrojraj Kale: Data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing — original draft.
Sewan Das Patle: Conceptualization, data curation, visualization, project administration, supervision, writing — review and editing.
Vijay Khawale: Plagiarism scan, data curation, visualization, writing — review and editing.
Sandeep Lutade: Data curation, visualization, writing — review and editing.

Data availability The data that supports the findings of this study are available within the article and proper references were provided.

Declarations

Ethics approval Not applicable
Consent to participate Not applicable
Consent for publication Not applicable
Competing interests The authors declare no competing interests.

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The submitted work is original and has not been published elsewhere in any form or language.

This manuscript is presented in “International Conference on Advances in Sustainable Research for Energy and Environmental Management (ASREEM-2021) on 06 August 2021. The conference is organized by Department of Chemical Engineering SVNIT Surat.