

Effect of Injection Timing on a Diesel Engine Fueled with Biomass to Liquid Diesel and *Spirulina* Microalgae Biodiesel Blends

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ABSTRACT

Due to fossil diesel's limited supply and environmental worries, scientific research on alternative fuels is gaining traction in a promising way. The significant lipid content of third generation microalgae oil makes it preferable over regular biodiesel sources. Currently, biomass to liquid (BTL) diesel, a sustainable fuel, is regarded as a novel fuel for diesel engines due to their drop in characteristics and enhanced engine performance compared to biodiesel. Hence, the authors aim to conduct a numerical investigation to trace the impact of neat BTL diesel and the blends of *Spirulina* microalgae biodiesel and BTL diesel on a diesel engine using Diesel-RK software. The performance, combustion, and emission attributes of the engine are explored for neat BTL diesel and for three separate blends produced by including 20, 40, and 60 vol% (BD80MB20, BD60MB40, and BD40MB60, respectively) of microalgae biodiesel into BTL diesel, and then the results are compared to those of conventional diesel. The parameters are measured for three different injection timings (ITs) of -1° , 4° , and 7° bTDC, keeping the swirl ratio constant at 1. BTL diesel is figured out to have a lower brake specific fuel consumption (BSFC) than neat diesel. However, the addition of microalgae biodiesel into BTL diesel raised the BSFC compared to pure BTL diesel. For all ITs, the brake thermal efficiency is higher for BTL diesel and other blends than conventional diesel. Reductions in ignition delay period, combustion duration, and peak heat release rate in premixed combustion are noticed for BTL diesel and remaining biofuel blends compared to neat diesel, leading to favorable combustion attributes. Additionally, the quantity of CO₂, smoke, and particulate matter in engine exhaust is decreased, although the emission of oxides of nitrogen rose while using BTL fuel and biodiesel/BTL fuel blends compared to regular diesel.

Keywords: BTL diesel, Microalgae biodiesel, Combustion, Emissions, Performance



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1. Introduction

While the demand for fossil fuels appears to be peaking in industrialized economies, it continues to expand over the world due to economic development and improvements in living standards. The transportation sector is one of the largest consumers of diesel because of its attractive properties to be used as automotive fuel. The substantial issue of fossil fuel depletion and a rise in fossil fuel costs are outcomes of gradual usage of fossil fuels to meet the rise in energy demand [1]. Additionally, the harmful substances found in exhaust gasses from the combustion of fossil fuels have significant adverse effects on the environment, contributing to deforestation, greenhouse gas emissions, and ozone depletion [2]. So, developing alternative fuels has become a crucial area of study that is essential for raising internal combustion engine efficiency and minimizing pollution. Biodiesel has been emerged as one of the most popular alternative fuels for vehicles because of its reduced emissions of hazardous air pollutants, nontoxicity, and biodegradable properties [3]. Crop or animal derived lipids or triglycerides are the sources of biodiesel, which is made from biological materials [4]. Out of the three generations of biodiesel feedstocks, microalgae, the third generation, is identified as the one with the greatest potential for future sustainable development. Microalgae has become one of the most tempting substitute sources of lipid for biodiesel synthesis due to their superior growth figures

and productivity over field crops, as well as their high photosynthetic efficiency in producing biomass [5]. Rajak et al. studied the output of a single cylinder compression ignition (CI) engine under the application of *Spirulina* biodiesel at different loadings while the compression ratio (CR) kept constant. Compared to neat diesel, the brake thermal efficiency (BTE) was found to be lesser for microalgae oil blends; however, the hazardous emissions of CO and hydrocarbons (HC) were substantially decreased for *Spirulina* biodiesel blends [6]. Nautiyal et al. conducted an experiment to observe the impact of biodiesel extracted from *Spirulina* platensis algae on the performance, combustion, and emission characteristics of a diesel engine using three blends of diesel and algae oil. The findings showed that heat release rate (HRR) and combustion duration (CD) with biodiesel are lower and longer, respectively, compared to diesel, and BTE is almost similar to diesel. The emissions of CO and HC showed a notable reduction for biodiesel and its blends in comparison to conventional diesel [7]. The behavior of a common rail CI engine fueled with *Spirulina* microalgae biodiesel was described in detail in the numerical investigation of Rajak et al. using Diesel-RK software. Biodiesel was found to decrease BTE by 2.73%, particulate matter by 60%, CO₂ emissions by 6.1%, and oxides of nitrogen (NO_x) by 0.5% [8]. Researchers are recently trying to modify the combustion and exhaust phenomena of CI engines through the inclusion of innovative fuels like

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biomass to liquid (BTL) diesel with diesel and biodiesel blends. BTL diesel is a synthetic fuel that is generated in two stages: first, biomass is gasified to form gaseous components, and then the resulting gases are turned into liquid fuel using the Fischer-Tropsch method [9].

Ogunkoya et al. examined the implications of diesel, biodiesel, and BTL fuels on three distinct engine loads in a single-cylinder diesel engine. The diesel engine's indicated work and mechanical efficiency were marginally reduced at low engine loads when BTL was used, but they rose at high engine loads. An improvement in emissions was also noted for all studied exhaust gas samples except for NO_x [10]. The impact of the inclusion of BTL diesel into diesel was explored numerically by Rimkus et al. for a direct ignition CI engine. BTL addition elevated engine efficiency and decreased the rate of CO₂ and HC emissions as well as brake specific fuel consumption (BSFC) [11].

The aforementioned discussion highlights the potential of BTL diesel and biodiesel made from *Spirulina* microalgae as CI engine fuel. However, there is a lack of study regarding the effect of applying diesel, microalgae oil, and BTL diesel combinedly in diesel engines. Motivated by the need, this paper presents a numerical study to observe the effect of using blends of diesel-*Spirulina* microalgae biodiesel-BTL diesel on the combustion, performance, and emission characteristics of a CI engine under varying injection timing (IT).

2. Methods and Materials

2.1 Test Fuel Properties

Spirulina is quite effective in the transesterification process, containing a number of fatty acids. Properties like density, viscosity, flash point, lower heating value, and contents of C, H, and O of *Spirulina* microalgae oil and BTL are collected from Ref. [6] and Ref. [12]. The five different combinations of fuel used are indicated as D100 (neat diesel), BD100 (neat BTL), BD80MB20 (a blend of 80 vol% BTL and 20 vol% microalgae biodiesel), BD60MB40 (a blend of 60 vol% BTL and 40 vol% microalgae biodiesel), and BD40MB60 (a blend of 40 vol% BTL and 60 vol% microalgae oil). Equations from 1 to 4 are used to determine the physio-chemical properties of the blends as per previous literature [13].

$$\rho_b = \sum_{i=1}^3 X_i \rho_i \quad (1)$$

$$\ln V_b = \sum_{i=1}^3 X_i \ln V_i \quad (2)$$

$$CN_b = \sum_{i=1}^3 X_i CN_i \quad (3)$$

$$HV_b = \sum_{i=1}^3 X_i \rho_i HV_i / \sum_{i=1}^3 X_i \rho_i \quad (4)$$

2.2 Engine Specification

A single cylinder 4-stroke diesel engine is designed in the Diesel-RK software to evaluate its performance numerically for the test fuels. Bore size is 13.97 cm, and stroke length is 15.24 cm. The diameter of the nozzle orifice is 0.196 mm. The engine has a total displacement volume of 2.34 L. A common rail fuel injector is used.

2.3 Numerical Model Equations

Diesel-RK is a professional software for engine simulation and optimization. It classifies engine cylinder as an open-type thermodynamic system. The software has the features of fuel consumption prediction, valve timing optimization, performance and combustion analysis, exhaust gas analysis, etc., on the basis of several simulation models and governing equations. Table 1 contains the numerical models applied during the simulation to evaluate the characteristics of the CI engine. Thermodynamic models are implemented to evaluate the performance attributes, and multi zone models are utilized to analyze the combustion phenomena of the engine. The concentration of NO_x in emission is predicted using the Zeldovich mechanism. Some empirical equations are applied for friction and heat transfer models. The governing equations utilized in the computation are arranged in Table 2. The readers are referred to Ref. [13] for details of the models and the equations.

Table 1 List of simulation models.

Parameters	Models	Ref.
Ignition delay	Tolstov's mechanism	[14]
Combustion	Multi-zone model	[15]
NO _x	Zeldovich mechanism	[16]
PM	Alkidas mechanism	[17]
Smoke	Bosch and Hartridge	[13]

Table 2 Governing equations used in simulation.

Mass balance equation:

$$\frac{dm}{dt} = \sum_k \dot{m}_k \quad (5)$$

where, $\dot{m}_k$ is the mass flow rate of the k^{th} species in kg/sec.

Energy balance equation:

$$\frac{d(mu)}{dt} = -p \frac{dv}{dt} + \frac{dQ_{ht}}{dt} + \sum_j \dot{m}_j h_j \quad (6)$$

where, $\frac{d(mu)}{dt}$, $p \frac{dv}{dt}$, $\frac{dQ_{ht}}{dt}$, and $\sum_j \dot{m}_j h_j$ denote the internal energy, displacement work, heat transfer, and enthalpy flux, respectively.

BSFC equation:

$$BSFC = \frac{\dot{m}_f}{P_b} \quad (7)$$

where, $\dot{m}_f$ and P_b state the mass flow rate (kg/s) and the brake power (kW,) respectively.

Heat release model of IDP:

$$\tau = 3.8 \times 10^{-6} (1 - 1.6 \times 10^{-4} \cdot n) \sqrt{\frac{T}{P}} \exp\left(\frac{E_a}{8.312T} - \frac{70}{CN+25}\right) \quad (8)$$

where, P , T , E_a , τ , CN , and n denote the pressure, temperature, activation energy of fuel, time in seconds, cetane number, and engine speed in rpm, respectively.

3. Results and Discussion

3.1 Combustion Characteristics

3.1.1 Ignition Delay Period

Ignition delay period (IDP) has a significant impact on the attributes of diesel engines. The IDPs of the fuel blends applied in the study varying the IT are presented in the fig. 1. For all IT, it is observed that the IDP of neat BTL is smaller than that of regular diesel.

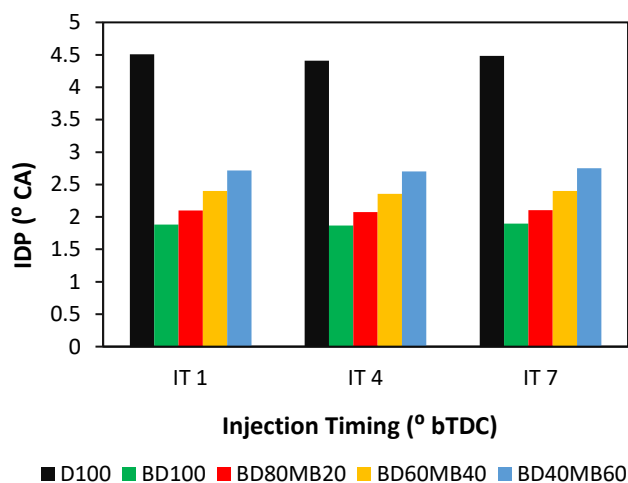


Fig. 1 Variations of IDP with IT.

The IDP is generally affected by the physico-chemical properties of fuel. As the cetane number of BTL diesel is higher than that of diesel, the IDP is found shorter for BTL diesel. In comparison to diesel, the IDP values are raised by 58.2%, 57.75%, and 57.68% for IT of 1, 4, and 7, respectively, while applying renewable BTL diesel.

However, the addition of biodiesel into BTL diesel resulted in an increase in the duration of ignition delay in all conditions. But neat diesel demonstrated the maximum IDP rather than any other blends. Lower IDP will reduce the PHRR in the premixed combustion zone.

3.1.2 Heat Release Rate

A vital aspect of combustion analysis in CI engines is the HRR, an assessment of the fuel's chemical energy conversion to thermal energy. Fig. 2(a-c) depicts the HRR for all blends at IT 1, 4, and 7, respectively. These figures illustrate that the peak heat release rate (PHRR) in the premixed combustion is lower for neat BTL diesel compared to ordinary diesel in all three cases. Reduced IDP of BTL is the reason behind this trend. A lower premixed air-fuel combination results from a lower IDP, which also lowers the PHRR in premixed combustion. The PHRR for BTL diesel in diffusion and late combustion is found lower with respect to neat diesel. In pre-mixed combustion zone, the PHRR of BTL diesel has shown a decrement of 42.92%, 40.36%, and 33.96% for IT 1, 4, and 7, respectively, compared to diesel.

Anyway, the addition of microalgae biodiesel in BTL diesel raises the PHRR of premixed combustion. The IDP goes high when biodiesel is added to BTL diesel.

3.1.3 Combustion Duration

The period during which from 10% to 90% of the air-fuel mixture combusts is known as the combustion duration (CD). The CD of the tested diesel engine for all five

fuel combinations is illustrated in the Fig. 3. The CD is seen to reduce for BTL diesel with respect to ordinary diesel. Inclusion of biodiesel in BTL diesel resulted in an increase in the values of CD gradually. But all the blends of fuel exhibited shorter CD than diesel. The lowest combustion duration is found for pure renewable BTL diesel, and the corresponding values are 27.8° CA for IT 1 and 4 and 28° CA for IT 7.

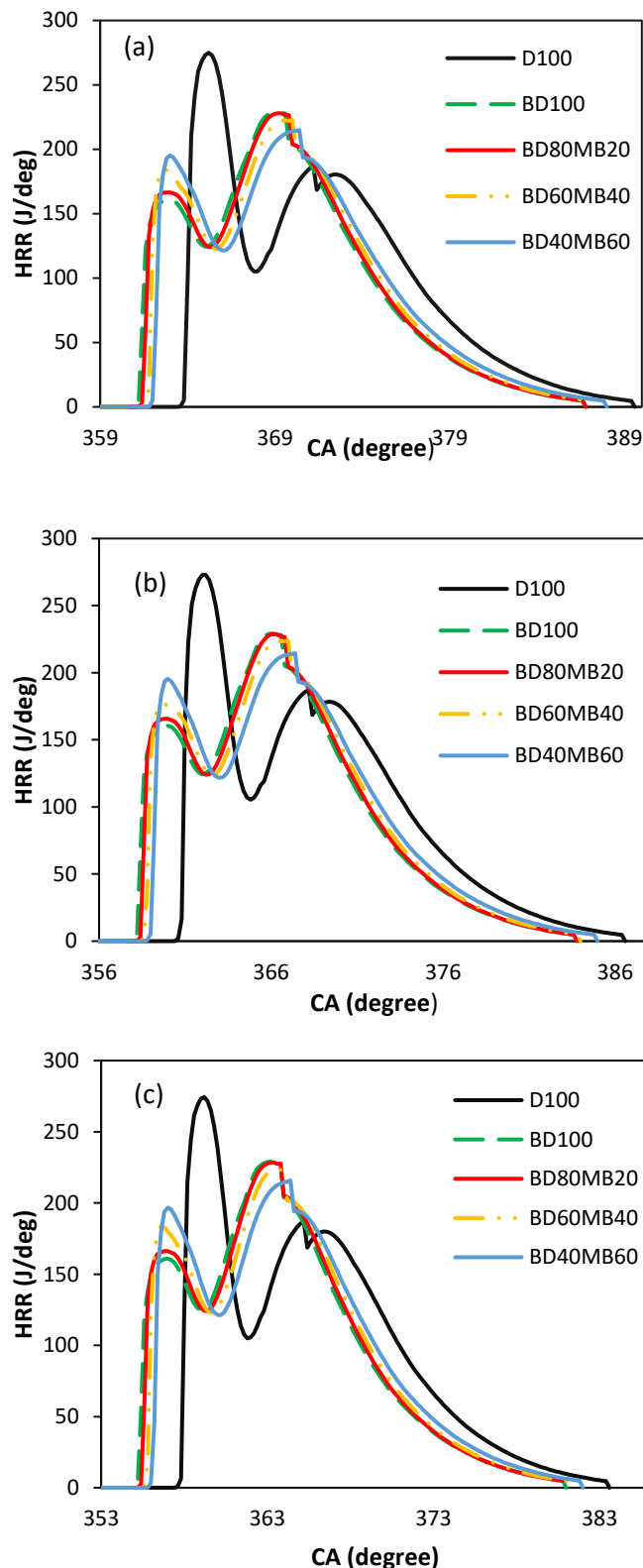


Fig. 2 Comparison of HRR of different fuel blends at (a)IT 1, (b) IT 4, and (c) IT 7 °bTDC.

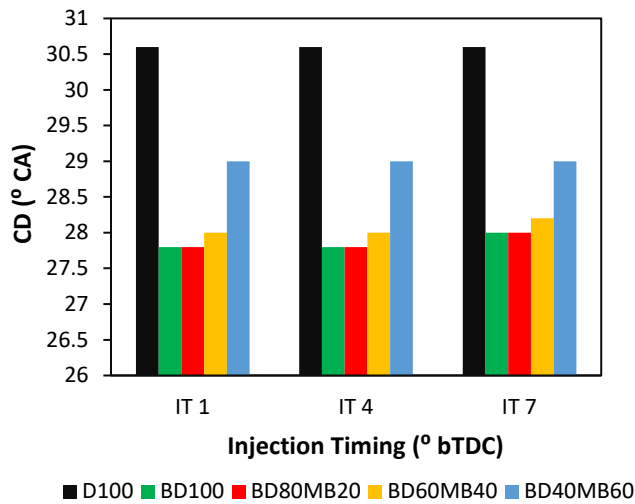


Fig. 3 Comparison of CD for various ITs.

3.2 Performance Characteristics

3.2.1 Brake Specific Fuel Consumption

The BSFC for different fuel blends at IT 1, 4, and 7 is depicted in Fig. 4. The BSFC raises with the increase in IT because of incomplete combustion and lower thermal efficiency. BSFC is found to reduce for all blends except BD40MB60 with respect to neat diesel. The lowest BSFC is 0.23468 g/KWh for BD100 at IT1.

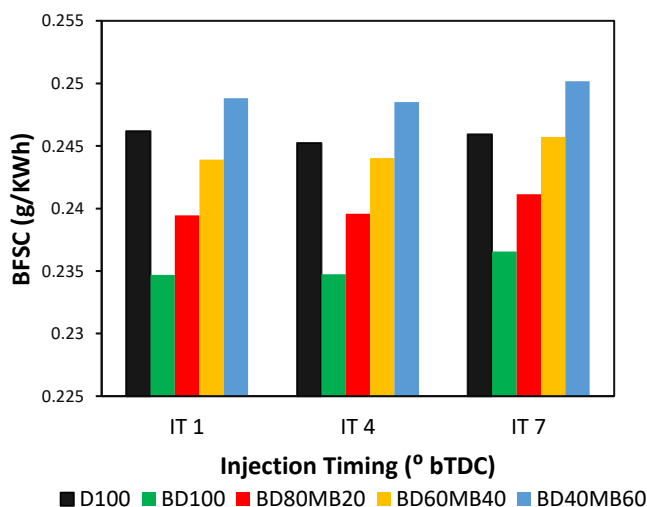


Fig. 4 Comparison of BSFC at various ITs.

3.2.2 Brake Thermal Efficiency

The most significant engine performance parameter, BTE, measures how well the engine converts fuel into energy. Fig. 5 illustrates the variation of BTE with injection timing for different test fuels. It shows that the BTE increases for every fuel blend in comparison to neat diesel. The values of BTE found lowest for IT 7. A downward trend in BTE is observed with the increment in IT, which is due to incomplete combustion and higher heat loss at higher IT. The engine's BTE appears to drop as the amount of microalgae oil in the blend increases. The BD100 at IT of 1 has the highest BTE, which is 34.41% in quantity. From the graph, it becomes apparent that as IT increases, the BTE for BTL diesel and the other three blends consistently decreases.

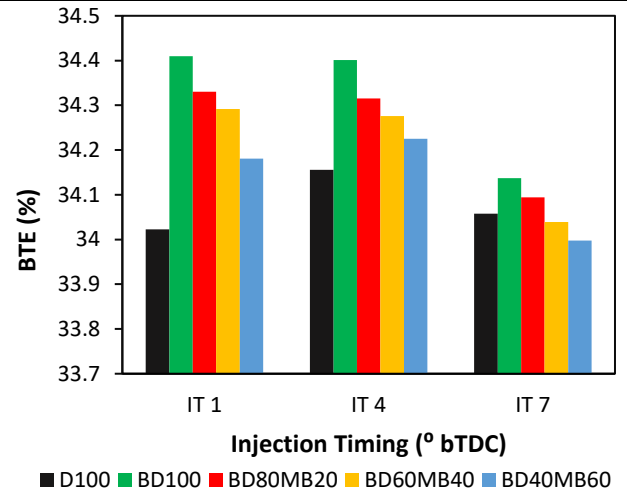


Fig. 5 Variation of BTE with IT.

3.3 Emission Characteristics

3.3.1 Carbon Dioxide

One of the terrible gases released by engines that negatively affects the environment worldwide is CO₂. The amounts of CO₂ released after the combustion of diesel, BTL diesel, and blends of biodiesel/BTL diesel for varying IT are presented in the Fig. 6.

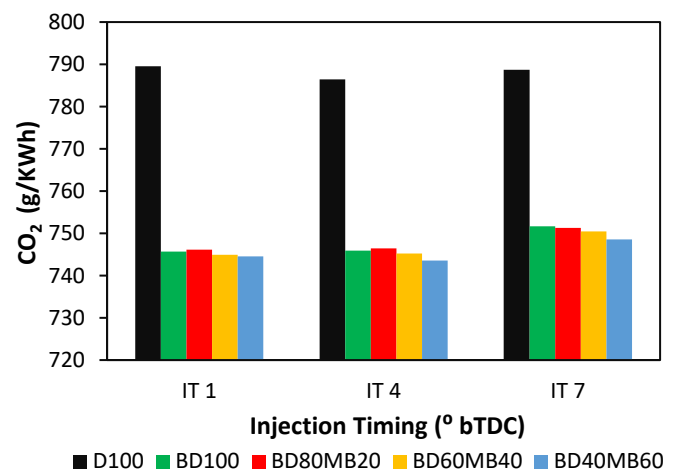


Fig. 6 Comparison of CO₂ emissions at different ITs.

It is clearly visible that the amount of CO₂ emissions is decreased for all fuel blends gradually compared to conventional diesel. The greater BSFC of diesel than BTL diesel caused the reduction in CO₂ emissions. Inclusion of biodiesel into BTL diesel reduced the exhaust of CO₂ more. The lowest CO₂ emission is observed for the BD40MB60 blend in the case of all the ITs. Therefore, upraising the proportion of microalgae oil in the BTL/biodiesel blend has resulted in a decrease in the emission of this harmful component. The highest amount of CO₂ is released by neat diesel at all IT, and the values are 789.53 g/KWh, 786.45 g/KWh, and 788.71 g/KWh for IT 1, 4, and 7, respectively.

3.3.2 Oxides of Nitrogen

The several oxides of nitrogen emitted from CI engines also put a negative impact on human health, polluting the air. Fig. 7 demonstrates the amounts of NO_x

emissions that resulted for different test fuels of the study. The amounts of NO_x emitted from burning neat diesel are 442.8 ppm, 574.22 ppm, and 723.95 ppm at IT 1, 4, and 7, respectively. The corresponding values of 100% BTL diesel are 740.52 ppm, 901.55 ppm, and 1091.8 ppm, accordingly.

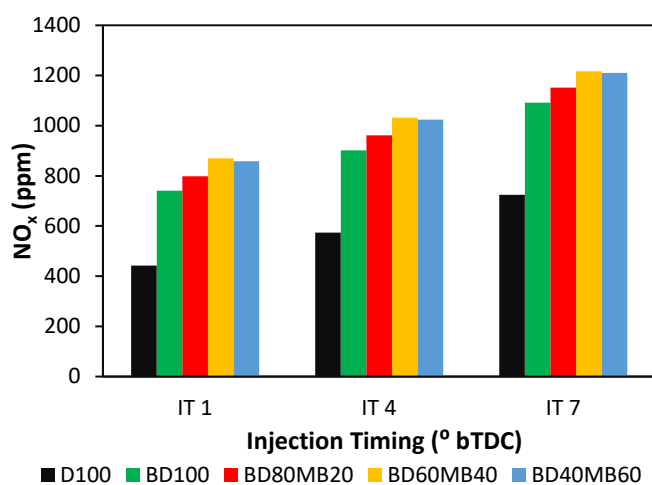


Fig. 7 Variation of NO_x emissions at different ITs.

Thus, the emission of NO_x is clearly higher for BTL diesel due to the increased combustion zone temperature of this renewable fuel. Incorporating biodiesel in BTL fuel raised the amount of NO_x more, and the highest values of this emission are observed for the BD40MB60 blend under all IT, and the quantities are 858.86 ppm, 1024.2 ppm, and 1210.1 ppm, respectively.

3.3.3 Particulate Matter

Particulate matter (PM) that is resulted from soot formed during combustion of fuel is another significant parameter in the analysis of emission attributes of CI engines. The graph in Fig. 8 shows the variation of release of PM while the considered fuels are burnt at different ITs.

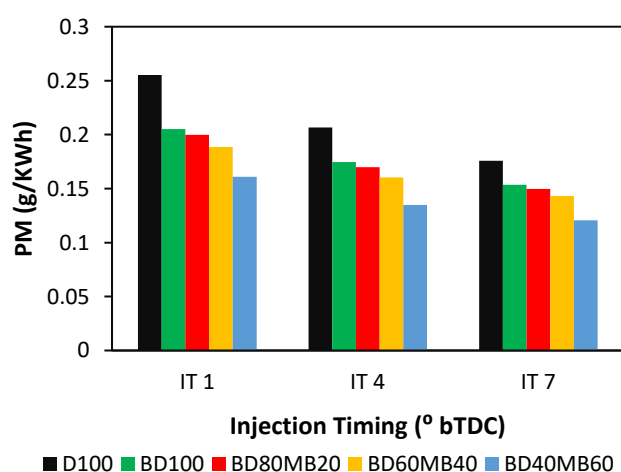


Fig. 8 Comparison of PM emissions with different ITs.

The graph indicates that the PM emission is lower for BTL diesel than ordinary diesel for all IT. The amounts of PM produced from the combustion of ordinary diesel are 0.25517 g/KWh, 0.20652 g/KWh, and 0.17571 g/KWh for IT 1, 4, and 7, respectively, whereas the values are 0.20517 g/KWh, 0.1745 g/KWh, and 0.15354 g/KWh respectively, for BTL diesel. The emission of PM using BTL diesel

decreased by 19.59%, 15.5%, and 12.62% for IT 1, 4, and 7 respectively, compared to diesel. However, fuel blends prepared by adding biodiesel into BTL diesel reduced more the PM emissions gradually. This trend is observed because of prolonged diffusion and late combustion periods of BTL and blends of BTL/biodiesel. The graph also indicates a reduction in PM for the fuel blends gradually while the IT rises.

3.3.4 Smoke

Fig. 9 shows the variation of smoke opacity in exhaust for the tested fuels. The graph indicates that the renewable BTL fuel emits smoke in lower quantities than pure diesel. Incorporation of microalgae biodiesel into BTL diesel showed a decrement in the amount of smoke emission compared to diesel.

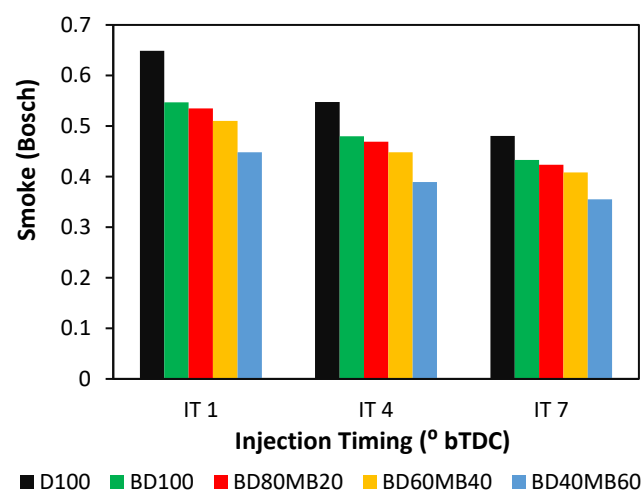


Fig. 9 Comparison of smoke emission at various ITs.

The emission of smoke seems to decrease gradually with the increase in the proportion of biodiesel in BTL diesel. The lowest amount of smoke is emitted by BD40MB60 blends, and the quantities are 0.44832 BSN, 0.38915 BSN, and 0.35511 BSN for IT 1, 4, and 7, respectively.

4. Conclusion

A computational investigation is carried out to evaluate the effect of BTL diesel and the inclusion of microalgae biodiesel in BTL diesel on the performance, combustion, and emission phenomena of the CI engine by varying the injection timing. A summary of the findings is the following:

- For all IT, BSFC is found to be lower for BTL diesel compared to neat diesel. A similar result is also shown by the BD80MB20 and BD60MB40 fuel blends. However, BD40MB60 has a higher BSFC than diesel. BTL diesel comes with the highest BTE compared to diesel and other test blends.
- The PHRR for BTL diesel in premixed combustion reduces by 42.92%, 40.36%, and 33.96% at IT 1, 4, and 7, respectively, in comparison to diesel. Inclusion of biodiesel into BTL diesel raises the PHRR of premixed combustion with respect to pure BTL diesel. However, all the test fuels have this PHRR smaller than that of diesel for all IT.
- The IDP is shorter for neat BTL diesel than diesel and any other test fuel. The IDP increases with the addition of

biodiesel, but still, neat diesel poses the maximum IDP for all IT. The CD is also seen to be lower for BTL diesel and other blends compared to neat diesel.

4. The CO₂ emissions by BTL reduce by 5.55%, 5.16%, and 4.7% at IT 1, 4, and 7, respectively, compared to diesel. The emission of NO_x rises gradually for both BTL diesel and biodiesel/BTL diesel blends with respect to diesel. A reduction of 19.59%, 15.5%, and 12.62% in PM emissions is shown by BTL at IT of 1, 4, and 7, accordingly, compared to neat diesel.

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NOMENCLATURE:

- bTDC*: before top dead center, °
BSFC: brake specific fuel consumption, g/KWh
BTE : brake thermal efficiency, %
IT : injection timing, °bTDC
PM : particulate matters, g/KWh
CA : crank angle, degree