STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Issue 5, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc/

Research JoPC

Performance, Emission, and Combustion Evaluation of Chlorella Vulgaris Biodiesel-Diesel Blends in a Compression Ignition Engine

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Abstract

This study examines, without modifying the engine, the performance, emissions, and combustion properties of biodiesel blends made from Chlorella vulgaris microalgae in a four-stroke, single-cylinder, water-cooled CI engine. The blends of biodiesel and diesel, designated B10, B20, B30, and B40, were 10%, 20%, 30%, and 40%, respectively. Of these, B20 showed the best efficiency-to-emissions ratio. Although it recorded the lowest brake specific fuel consumption of 0.232 kg/kWh, indicating superior fuel utilisation, its brake thermal efficiency of 27.89% was marginally lower than diesel's 30.12%. According to combustion analysis, B20 demonstrated efficient combustion with a maximum heat release rate of 49 J/°CA and a peak cylinder pressure of 66 bar. Its 13.9°CA ignition delay was almost identical to that of diesel (13.8°CA). In terms of emissions, B20 kept NO_x levels (853 ppm) near diesel levels while drastically lowering carbon monoxide (0.99%) and unburned hydrocarbons (96 ppm). Because biodiesel is oxygen-rich, the filter smoke number (FSN = 6) also showed decreased smoke opacity. All things considered, B20 proved to be the best blend, providing stable combustion, high thermal efficiency, and lower emissions, making it a practical and environmentally responsible substitute for traditional diesel.

Keywords: Diesel, biodiesel, engine performance, combustion, transesterification

INTRODUCTION

Global research efforts are focused on developing sustainable and alternative energy sources for the transportation sector due to the rapidly depleting fossil fuel reserves and the growing environmental concerns surrounding greenhouse gas (GHG) emissions [1,2]. Diesel engines continue to be a popular power source in industrial and transportation settings because of their high durability and efficiency, but their reliance on fuels derived from petroleum greatly increases air pollution and contributes to climate change [3,4]. In this regard, biodiesel made from non-edible and renewable feedstocks has become a viable alternative fuel that can partially replace traditional diesel while having less of an adverse effect on the environment [5–7].

Microalgae have drawn more attention than other biodiesel feedstocks because of their high lipid content, quick growth rate, and capacity to flourish in non-arable areas without posing a threat to food crops [8,9]. A lot of research has been done on

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Received Date: August 05, 2025
Accepted Date: August 25, 2025
Published Date: September 05, 2025

Citation: Alagala Harikrishna, B. Chandra Mohana Reddy. Performance, Emission, and Combustion Evaluation of Chlorella vulgaris Biodiesel-Diesel Blends in a Compression Ignition Engine. Journal of Polymer & Composites. 2025; 13(5): 339–354p. DOI: https://doi.org/10.37591/JOPC.v13i05.227099

Chlorella vulgaris in particular as a third-generation biofuel feedstock because of its advantageous fatty acid composition, which results in desirable fuel qualities like increased oxygen content, biodegradability, and lower sulphur emissions [10–12]. Using catalytic and nanocatalytic transesterification techniques, several studies have successfully converted Chlorella vulgaris biomass into biodiesel, producing fuel with properties similar to those of regular diesel [13,14].

Compression ignition (CI) engines powered by microalgal biodiesel and its diesel blends have shown promising results in experimental studies. Despite a minor penalty in nitrogen oxides (NOx), blends of Chlorella biodiesel with diesel (B10–B40) have demonstrated acceptable brake thermal efficiency (BTE), improved combustion due to inherent oxygenation, and significant reductions in unburned hydrocarbons (HC), carbon monoxide (CO), and particulate matter emissions [15–18]. Additionally, recent studies have emphasised how alcohol co-blending and nanoadditives (such as butanol and pentanol) can improve atomisation, optimise ignition delay, and reduce the production of NOx [6,14]. The potential of chlorella-based biodiesel to enhance sustainability indices and engine performance under ideal operating conditions is further demonstrated by thermodynamic and exercise evaluations [7,15].

Large-scale production, blend optimisation, and maintaining consistent performance under changing load and ambient conditions are still obstacles in spite of these advancements. There aren't many thorough studies on mid-range blends (B20) that contain Chlorella vulgaris biodiesel, particularly when it comes to the combined performance, combustion, and emission analysis of contemporary diesel engines. To promote global decarbonisation initiatives in the transportation sector and hasten the shift to sustainable fuels, these gaps must be filled.

Goals of the Current Study

The goal of this study is to fill in these gaps by testing B10, B20, B30, and B40 mixtures of Chlorella vulgaris biodiesel and mineral diesel in the lab. The goals include testing engine performance metrics (BTE, BSFC) at loads ranging from 0% to 100%. Looking at the parameters of combustion, such as cylinder pressure, heat release rate, and ignition delay. Measuring the amount of CO, HC, CO_2, NO_x, and filter smoke number (FSN) in the exhaust.

The study's results show that B20 has the best balance of performance, combustion efficiency, and emissions, making it a good candidate for replacing some diesel fuel in CI engines.

LITERATURE SURVEY

Al-lwayzy et al. [1] used blends of Chlorella protothecoides biodiesel to investigate the performance of diesel engines. According to their research, CO, HC, and smoke emissions were much lower, but brake thermal efficiency was on par with diesel fuel. The potential of algal biodiesel in CI engines was demonstrated by the slight increase in NOx emissions caused by the higher combustion temperature.

Mathimani et al. [2] looked into using Chlorella BDUG 91771 grown outdoors to produce biodiesel for CI engines. The biodiesel burned steadily and met ASTM requirements. While NOx emissions slightly increased, CO, HC, and smoke emissions were found to have decreased. Their research demonstrated the feasibility of using outdoor cultivation to produce biodiesel.

Elkelawy et al. [3] tested diesel/n-pentane–algae biodiesel blends in DI diesel engines. Adding n-pentane made the mixture more volatile and improved premixed combustion. Their results showed that CO and HC emissions were lower and that the performance was almost the same as diesel. This study showed how useful co-solvents can be for making biodiesel work better.

Rajak et al. [4] examined spirulina-based biodiesel blends in diesel engines. The engine didn't work as well as it did with diesel fuel. But the amount of CO and smoke that came out was much lower, while the amount of NOx that came out was higher because the combustion temperatures were higher. Their research showed that spirulina biodiesel is good for the environment.

Sanli et al. [5] performed a thermodynamic examination of microalgae biodiesel mixtures under diverse ambient conditions. They said that compared to diesel, they had better exergy efficiency and made less entropy. The study found that biodiesel blends worked well at different loads and temperatures. Their results showed that the amount of oxygen in biodiesel was related to gains in efficiency.

Harikrishna et al. [6] compared B20–pentanol and B20–butanol–diesel blends in CI engines. The alcohols made atomisation better and helped the combustion process finish. The results showed that CO and HC emissions went down a lot, while NOx emissions only went up a little. Their research validated alcohols as efficacious biodiesel augmenters.

Raja et al. [7] conducted energy and exergy analyses on algae biodiesel blends in direct injection engines. Compared to fossil diesel, higher exergetic efficiency and sustainability indices were reported. Biodiesel mixtures also showed good thermodynamic performance. Their research stressed optimising blends for better efficiency.

Al-Ansari et al. [8] examined the energy-exergy performance of Chlorella vulgaris biodiesel. Results showed that it had better exergy efficiency and used less fuel than diesel. Their research showed how using biodiesel can help with thermodynamics. The study showed that biodiesel is a good choice for a long-term alternative.

Mao et al. [9] investigated biodiesel made from Chlorella vulgaris in nonroad diesel engines. Their experiments revealed lower smoke and particulate matter levels without significant efficiency losses. Despite acceptable performance trade-offs, combustion stayed constant. Their research confirmed the use of algae-based biodiesel for off-road purposes.

Ratomski et al. [10] examined biofuel blends derived from algal biomass in transportation engines. Their results showed that the torque and power delivery were stable, and that CO, HC, and CO_2 emissions were lower. The study focused on how biodiesel can help lower greenhouse gas emissions. Their findings corroborated biodiesel's contribution to sustainable transportation.

Nematian et al. [11] made biodiesel from Chlorella vulgaris with a nano-biocatalyst. Conversion yields, fuel stability, and the ability to reuse catalysts all improved a lot. Biodiesel that was made showed better ignition quality and stability. Their research showed how nanotechnology can help make biodiesel more efficiently.

Praveen et al. [12] examined nanoadditive-enhanced Chlorella vulgaris biodiesel blends in compression ignition engines. The results showed that the brake thermal efficiency was better than with neat biodiesel. There was a small rise in NOx, but CO and HC emissions went down a lot. Their results showed how nanoparticles can improve fuel blends.

Ramesh et al. [13] examined methyl esters derived from Chlorella vulgaris oil. The biodiesel met ASTM standards for density, viscosity, and cetane number. The fatty acid composition showed that the material could catch fire easily, but it also showed that it would be hard to flow when cold. Their findings confirmed the fuel's suitability for CI engines.

Thangamani et al. [14] examined biodiesel derived from Chlorella vulgaris combined with TiO_2 nanoparticles in diesel engines. The additives made combustion more efficient and cut down on CO, HC, and smoke emissions. The thermal efficiency of the brakes also got a lot better. Their research validated the contribution of nanoparticle additives to performance enhancement.

Tiwari et al. [15] conducted energy-exergy analyses on microalgae biodiesel blends. The results showed that it had a higher exergy efficiency and a lower irreversibility than diesel. B20 blends gave the best balance between emissions and efficiency. Their results showed that biodiesel is thermodynamically sustainable.

Subramaniam et al. [16] investigated algae biodiesel blends in direct injection diesel engines. Compared to diesel, the results showed that CO, HC, and smoke emissions were lower. The lower heating value was blamed for small losses in efficiency. Their research demonstrated algae biodiesel as an environmentally sustainable alternative fuel.

Venu et al. [17] investigated Chlorella emersonii biodiesel in CI engines, emphasising unregulated emissions. They saw that the emissions of aldehydes and PAHs were lower than those of diesel. Combustion stayed stable with very little effect on performance. Their research showed that biodiesel is better at cutting down on harmful exhaust fumes.

Kale et al. [18] investigated the performance of CI engines utilising algal biodiesel blends. Biodiesel's oxygenated nature made combustion more efficient. There was a big drop in CO and HC emissions, but a small rise in NOx emissions. Their results showed that biodiesel can lower emissions.

Zibarev et al. [19] studied the lipid composition of different Chlorella strains to see if they would be good for making biodiesel. C. vulgaris had a lot of lipids and fatty acids that were good for health. The biodiesel that was made had good cetane and oxidative stability. Their results confirmed that choosing the right strain is important for making biodiesel.

Sabre et al. [20] investigated Chlorella vulgaris subjected to heavy metal stress to promote lipid accumulation. The amount of lipids produced went up a lot, which increased the yield of biodiesel. The biodiesel that was made had good physical and chemical properties. Their research proposed cultivation strategies for the production of high-quality biodiesel.

MATERIALS AND METHODS

Biodiesels have gotten a lot of attention as eco-friendly alternative fuels that can be used in diesel engines without needing to make big changes. However, there are still problems with the current methods, like exhaust leaks, worries about how to handle fuel, and the need to make sure that the engine layout is compatible. To get around these problems, it has been suggested that diesel-algae biodiesel blends, such as B10, B20, B30, and B40, be used to test engine performance, emissions, and how well they burn. There are still a few big technical problems that need to be solved in the production of algae biofuel. These include strain isolation, finding and using nutrients, scaling up production, harvesting efficiently, developing co-products, extracting fuel, refining it, and using leftover biomass. To solve these problems, biodiesel is made by blending it with regular diesel in large amounts using microwave-assisted transesterification. Biodiesel has a higher cetane number, which helps it ignite better, but it also has a higher viscosity and a lower calorific value. Higher viscosity can make it harder for fuel to atomise and use more energy to inject. Mixing biodiesel with diesel in amounts like B10, B20, B30, and B40 makes the fuel flow better and gives it more energy. The fuel blends were tested, and B10 to B40 were chosen for more engine testing without needing to change any hardware.The B20 blend, in particular, had a much higher brake thermal efficiency (BTE) because it burned better and released heat more effectively under different load conditions. Tests on a 3.5 kW, single-cylinder, four-stroke, water-cooled diesel engine (bore 87.5 mm, stroke 110 mm, CR 17.5, 661.45 cc displacement) showed that algae biodiesel blends not only cut down on carbon monoxide (CO), unburned hydrocarbons (UBHC), and smoke emissions, but they also kept the combustion stable. Nitrogen oxide (NO_x) emissions went up a little as the biodiesel content went up, but they stayed within acceptable limits. So, this study shows that algae-based biodiesel blends, especially B10 to B40, can be used in real life to help meet future energy needs with less harm to the environment and more sustainability.

Chlorella Vulgaris Algae (B20) Synthesis and Characterization

Chlorella vulgaris was chosen to make biodiesel because it is easy to grow, reproduces quickly, and absorbs light well, especially in the red spectrum, because it has a lot of pigments. Figure 1 shows that the harvested culture of Chlorella vulgaris is a single-celled aquatic green alga that is very good at making lipids and is often used in biofuel research. This species was chosen because it is a photosynthetic eukaryote with compact growth habits and dense cellular structures. It can make a lot of fatty acids when conditions are just right. The first step in growing Chlorella vulgaris was to move the cells from solid agar medium to 200 mL of sterilised liquid nutrient solution. Both the glassware and the culture media were autoclaved for 20 minutes at 121°C to kill any germs that might be there. Figure 2 shows the algal biomass that was taken out. When doing manual extraction, being outside increases the chance of bringing in unwanted contaminants. Touching biomass and not cleaning it well enough can cause skin oils, environmental particles, or microbes to get into it. So, to keep the samples safe, strict aseptic techniques were used, such as using clean equipment and handling the samples carefully.

Over the course of 52 days, a semi-continuous cultivation strategy was used in an open raceway pond with a working capacity of 1200 litres. The main source of nutrients was commercial fertiliser. The system was able to produce the most biomass, about 19.61 g/m²/day. Alum-based flocculation was used to harvest the biomass, which was then dried in the sun and then in the microwave. Next, the dried algae were filtered through cotton cloth filters to get the final feedstock. During the growth process, microalgae were kept at a steady temperature of 24°C and exposed to cool white LED light at a level of 150 µmol/m²/s. Passing air through silicon tubing with a 20-micron filter and adding 1% carbon dioxide (v/v) made sure that aeration happened.To keep the mixing even, the flasks were placed on a rotary shaker that spun at 120 rpm.

BG11, a standardised algal nutrient medium, was used for the first six days to get the best growth. This medium has a lot of important nutrients for algae growth, such as nitrogen, phosphorus, trace metals, and vitamins. The culture was changed to nitrogen-deficient BG11 for the next six days to encourage the buildup of lipids. When the algae reached the right stage of growth, it was harvested by spinning it at 4000 rpm for 40 minutes and then rinsing it twice with deionised water to get rid of any dirt. The sulfo-phospho-vanillin test was used to measure the lipid content, and the highest yield was 35% of the dry weight.

Solvent extraction methods were used to break down the cell walls so that the lipids inside could be accessed. To get the lipids back, a controlled amount of ethanol, water, and hexane were used in a liquid-liquid extraction process. Ten grammes of dried biomass were mixed with 30 mL of ethanol (96% v/v) in a 250 mL round-bottom flask and heated at 60°C for 12 hours under reflux. Magnetic stirring kept the agitation going all the time. A Dwyer flow meter set to 1.5 mL/min controlled the flow of air. It took 96 hours for the cultures to grow from the lag phase to the exponential growth phase. The cells were separated using a centrifuge that ran at 3000 rpm for 15 minutes. After being separated, the cells were washed with distilled water and put back into 400 mL of fresh BG11 medium.

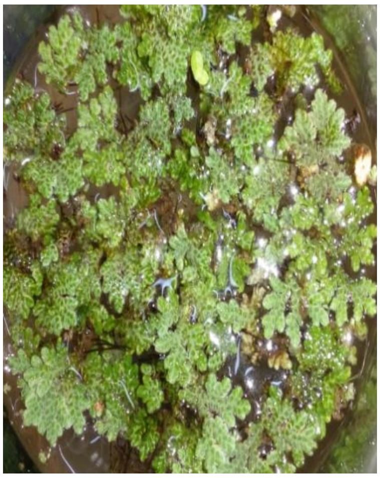

Figure 1. Picture of algae.

Figure 2. Getting algae out.

Figure 3. Raw algae oil.

Figure 4. Esterification process.

It kept track of the cell density by measuring the optical density (OD) at 660 nm. We put the same amount of biomass into 500 mL flasks for large-scale experiments. The new cultures began with an OD of 0.1, and the cells were allowed to grow until they reached the late exponential phase. We used an oil bath reactor with a reflux condenser and magnetic stirring at 300 rpm to transesterify dry Chlorella biomass in situ. First, 10 grammes of dry biomass were mixed with different amounts of methanol and sulphuric acid. The amounts were 5%, 10%, 15%, and 20% by weight.The reaction took place at 60°C for four hours.

After the reaction, vacuum filtration was used to separate the biomass. A rotary evaporator was used to get back the extra methanol. To get rid of polar impurities that didn't react, 100 mL of hexane was added to the organic layer with fatty acid methyl esters (FAMEs). We then used a separating funnel to separate the phases, which left us with the crude biodiesel as the hexane-soluble fraction.

To make this fraction even better, the hexane solvent was evaporated in a rotary evaporator. Figure 3 shows that the raw algal oil, or crude biodiesel, was a golden yellow colour and had a semi-viscous texture. It also had triglycerides, free fatty acids, and natural antioxidants in it.

Figure 4 shows the last step in the process, where the extracted lipids were turned into usable biodiesel through the reaction of methanol and sodium methoxide, which acted as the catalyst and solvent, respectively. The best conditions for the reaction were a temperature of 55°C, a molar ratio of 6:1 (methanol to oil), a catalyst loading of 1.5 wt%, and a reaction time of 150 minutes, with stirring at 975 rpm. Under these conditions, the reaction produced 97.4% biodiesel.

The finished biodiesel met ASTM D6751 standards for physical and chemical properties, such as viscosity, flash point, density, and cetane number. The biofuel that came out of this process, B20 (20% biodiesel and 80% diesel), was thought to be good for mixing with regular diesel. It was then used in performance, combustion, and emission studies in compression ignition (CI) engines at different blend ratios (B10, B20, B30, and B40).

Changing The Fuel and Choosing Binary Blends

The first step in making the biodiesel blends was acid esterification, which used 1.5% sulphuric acid and 20% methanol at 64°C for 15 minutes. This brought the amount of free fatty acids down to less than 2%. Next, base transesterification was done at 64°C for 10 minutes with 1% potassium hydroxide and a methanol-to-lipid molar ratio of 10:1. Gravity settling and washing with hot distilled water were used to separate biodiesel from glycerol and extra alcohol. Sodium sulphate was used to get rid of the moisture, and then the biodiesel was filtered and put in airtight borosilicate bottles.Four binary blends were prepared:

- *B10*: 10% biodiesel + 90% diesel
- *B20*: 20% biodiesel + 80% diesel
- *B30*: 30% biodiesel + 70% diesel
- *B40:* 40% biodiesel + 60% diesel

The sample is mixed each blend for 30 minutes at 500 rpm and then stored it for 12 hours to make sure it was uniform and stable.

FUEL PROPERTY CHARACTERIZATION OF DIESEL AND MICROALGAE BIODIESEL BLENDS

Table 1 shows the physical and chemical properties of diesel, raw Chlorella vulgaris algae oil, and their mixtures (B10, B20, B30, and B40). The more algae oil there was in the blends, the denser the fuel became. This is because raw Chlorella vulgaris algae oil has a higher density (876 kg/m³) than diesel (828 kg/m³). The density rises from 832.8 to 847.2 kg/m³ as the biodiesel fraction goes from B10 to B40. Higher fuel density can improve volumetric energy content but may adversely affect atomization quality, spray penetration, and air–fuel mixing in compression ignition engines. The densities of all the blends, on the other hand, are still within the ASTM D975 acceptable range for diesel fuels.

Kinematic viscosity is an important factor that affects how fuel sprays, how well it breaks up, and how well it burns. The viscosity of raw algae oil (4.76 cSt) is much higher than that of regular diesel (2.39 cSt). As the blending goes on, the viscosity of the blends slowly rises from 2.63 cSt for B10 to 3.34 cSt for B40. This shows that the viscosity responds linearly to the concentration of algae oil. This increase, while small, is still within ASTM D445 standards for diesel fuel when properly controlled. It also makes sure that the flow characteristics are manageable and the injectors are compatible, especially for B10 and B20. The higher viscosity may help with better lubrication and less wear, but it may also slow down atomisation a little at higher blends like B40.

With more algae oil, the flash point of the fuels—a very important safety feature for storage and handling—went up a lot. Because it wasn't very volatile, raw algae oil had a high flash point (160°C). The flash point of blended fuels went up from 57.4°C for B10 to 91.6°C for B40, which is higher than the 46°C for diesel. The blends have higher flash points, which makes them safer to store because they are less likely to catch fire than neat diesel. These values are much higher than the minimum flash point for diesel fuel, which is usually over 52°C. This shows that the fuel is more thermally stable and safer to handle.

Fire point values go up steadily with the amount of biodiesel, just like flash point values. The fire point for diesel was 52°C, for B10 to B40 it was between 63.8°C and 99.2°C, and for raw algae oil it was 170°C. This steady rise makes the thermal safety margins of algae oil blending even stronger.

Cloud and pour points are very important for figuring out how something will flow when it's cold. Raw algae oil has a cloud point of 5°C and a pour point of −7°C, which makes it hard to work with at low temperatures. When mixed with diesel, these values go down. For example, B10 and B20 have cloud points of 0.5°C and 1.0°C, respectively, and pour points of −14.2°C and −13.4°C, which are much better than those of raw algae oil. Because diesel dilutes the oil, even B40 has good cold flow performance (cloud point: 2°C, pour point: −11.8°C). These results show that algae oil and diesel blends up to B40 can be used in moderate climates without needing to add anything to improve cold flow.

As the amount of algae oil in biodiesel goes up, the calorific value goes down. This affects the engine's power output and thermal efficiency. Diesel has a calorific value of 42 MJ/kg, while algae oil has a calorific value of 39.67 MJ/kg. The blends show a slow drop, from 41.77 MJ/kg for B10 to 41.07 MJ/kg for B40. Even though this drop is significant, it is still manageable and can be made up for by the fact that oxygenated fuels burn better, especially when they are mixed with lower amounts of other fuels.

Table 1. Fuel properties of diesel, Raw Chlorella vulgaris algae oil, and their blends.

Fuel blend	Density (kg/m^3)	Kinematic viscosity (cSt)	Flash point (°C)	Fire point (°C)	Cloud point (°C)	Pour point (°C)	Calorific value (MJ/kg)	Cetane number
Diesel (D100)	828	2.39	46	52	0	−15	42	52
Raw chlorella vulgaris algae oil	876	4.76	160	170	5	−7.0	39.67	55.8
B10	832.8	2.63	57.4	63.8	0.5	−14.2	41.77	52.38
B20	837.6	2.86	68.8	75.6	1	−13.4	41.53	52.76
B30	842.4	3.1	80.2	87.4	1.5	−12.6	41.3	53.14
B40	847.2	3.34	91.6	99.2	2	−11.8	41.07	53.52

The cetane number, which tells you how well fuel ignites, went up as more algae oil was mixed in. The cetane number of raw algae oil was 55.8, which is higher than the cetane number of diesel (52.0). This means that it ignited faster and had less of a delay before ignition. The blends had cetane numbers between 52.38 (B10) and 53.52 (B40), which made the engine run more smoothly and more efficiently. This rise may help lower noise and emissions from combustion, especially in blends up to B30. Overall, the fuel characterisation data show that B10 and B20 blends strike a good balance between better safety, combustion quality, and cold flow behaviour, with only small losses in energy content. These blends meet ASTM standards and can be used in compression ignition engines without major changes to the engine. In colder climates, blends with more than 30% B30 may need small changes or preheating of the fuel because of viscosity and cold flow limits. So, the chosen blends are in a good position to support sustainable fuel alternatives while still being reliable and performing well.

EX PERIMEN TAL SETUP

The setup for the proposed engine test is as shown in Figure 5. The experimental study used a single-cylinder, four-stroke, direct injection compression ignition (CI) engine that ran at a constant speed of 1500 rpm and produced 3.7 kW of power. The engine that was used had a compression ratio of 17.5:1 and was cooled by water to keep the temperature stable during testing. The most important geometric details were a cylinder bore of 87.5 mm, a stroke length of 110 mm, a connecting rod length of 234 mm, and a total swept volume of 661.45 cm^3. Fuel injection timing was set at 23° before top dead centre (bTDC), and the fuel injection pressure stayed at 200 bar. This is how to set up an engine test. A standard burette setup was used to find out how quickly the fuel was used and a differential pressure-based air flow sensor to find out how quickly the air was flowing. Carefully placed K-type (chromium-alumel) thermocouples in key spots on the engine to keep an eye on the temperature.

Figure 5. Setup for the engine test.

A calibrated rotameter was used to control and measure the flow of cooling water, which kept the engine's temperature stable.The engine was connected to an eddy current dynamometer so that different load conditions could be used during the tests. An AVL Digas 444 five-gas analyser was used to look at emissions by measuring the amounts of carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (HC), nitrogen oxides (NO_x), and oxygen (O_2) in the exhaust gases. An AVL 415SE smoke meter was used to find out how opaque the smoke was, which is measured as Filter Smoke Number (FSN).

A pressure sensor connected to a data acquisition system recorded the combustion parameters. A smoothing factor of 2 is used to record the pressure inside the cylinder for 10 engine cycles in a row. The combustion model was based on air that had a density of 1.17 kg/m³, an adiabatic index of 1.41, and a polytropic index of 1.37. A crank angle encoder that made 360 pulses per revolution made sure that timing measurements were correct.

A computer-based monitoring interface was used to connect the fuel and air supply systems. Other experimental constants were a 20 mm orifice diameter, a 0.60 discharge coefficient, an 185 mm dynamometer arm length, and a 12.4 mm fuel pipe diameter. The temperature of the room where the tests were done stayed around 27°C. The baseline diesel fuel had a density of 825 kg/m³ and a calorific value of 42,200 kJ/kg. The engine was tested using conventional diesel and blended fuels prepared by mixing diesel with 10%, 20%, 30%, and 40% transesterified Chlorella vulgaris algae oil, corresponding to B10, B20, B30, and B40, respectively. Each blend was evaluated under varying engine load conditions to assess performance, combustion behavior, and emission characteristics under real-world operating scenarios.

RESULTS AND DISCUSSIONS

This part gives a full analysis of the experimental results, looking at how well the diesel engine worked, how much it emitted, and how it burned when it was fuelled with B10, B20, B30, and B40 biodiesel blends. There is also a thorough comparison to show that the chosen blends can be used and work well.

Performance Metrics of the Effect of Diesel-Biodiesel on Diesel Engine

Figure 6 shows that BTE goes up with engine load for all fuels because combustion works better at higher pressures and temperatures. Diesel (D100) had the greatest BTE (30.12%) because it has a higher calorific value (~43 MJ/kg) and is more volatile. B20 was the best biodiesel blend, with a BTE of 27.89%. This was because it had more oxygen, which made it burn better. B30 (27.71%) and B40 (27.26%) likewise had stable combustion, but their BTE was a little lower because their viscosity and density were higher, which made it harder for the fuel to atomise and vaporise. Still, none of the blends knocked or misfired, and they all worked well.

Figure 7 shows that BSFC goes down when the engine load goes up for all fuels. This is because the combustion gets better and the temperatures inside the cylinders go up. At full load, diesel (D100) had a BSFC of 0.24 kg/kWh, but B20 had a lower value of 0.232 kg/kWh. This means that B20 used the fuel better, even though it had a lower calorific value. This is because B20 has a lot of oxygen in it (around 11 wt%), which makes burning more efficient. B30 (0.245 kg/kWh) and B40 (0.262 kg/kWh) had higher BSFC because they were thicker and less volatile, which made atomisation worse and combustion incomplete. These impacts are stronger at lower loads, when the cylinder temperatures aren't high enough for good burning.

Emission Analysis

Figure 8 shows that CO emissions go up when the engine load goes up because the mixes are richer and the oxidation periods are shorter. At maximum load, diesel (D100) had a CO level of 0.96%. B20, on the other hand, had a CO level of 0.99%, which is just a 3.1% increase. This is because B20 has higher oxygen (~11 wt%), which helps combustion. B30 and B40 acted differently depending on the load. B40 reached its highest level of 0.45% CO at 50% load because the high viscosity and low volatility made it hard for the atoms to mix and burn completely. But when it was fully loaded, B40's CO level dropped to 0.94%, which was good because the increased temperatures made oxidation happen faster. On the other hand, B20 kept its CO emissions stable and mild across all loads, which shows that the combustion was efficient and balanced.

Figure 9 shows that all fuels release more CO_2 when the engine is under more load. This is because combustion is better at higher temperatures and pressures. Diesel (D100) had the lowest CO_2 level (7.92%) at full load because it has a high calorific value and a low BSFC. B20 released a little more CO_2 (8.12%) because its structure is rich in oxygen (~10–11 wt%), which makes carbon oxidation easier, even if it has a lower heating value. B30 and B40 had even higher CO_2 emissions, with B40 reaching 8.63%. This was mostly because they had a higher BSFC, which meant that more fuel mass was consumed for every unit of power. This shows that combustion is efficient, but it also means that more fuel is used because the viscosity makes it harder for the fuel to break down.

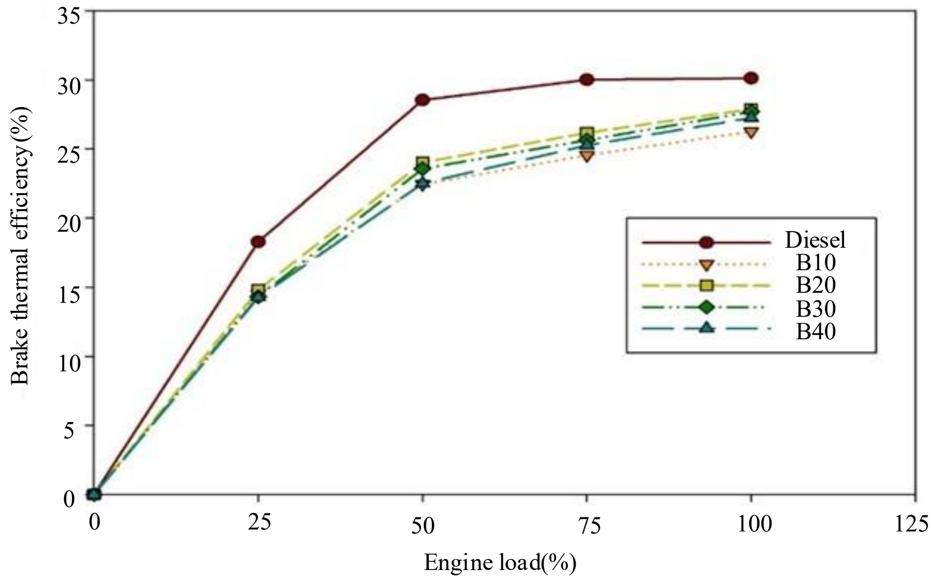

Figure 6. Brake thermal efficiency Vs engine load.

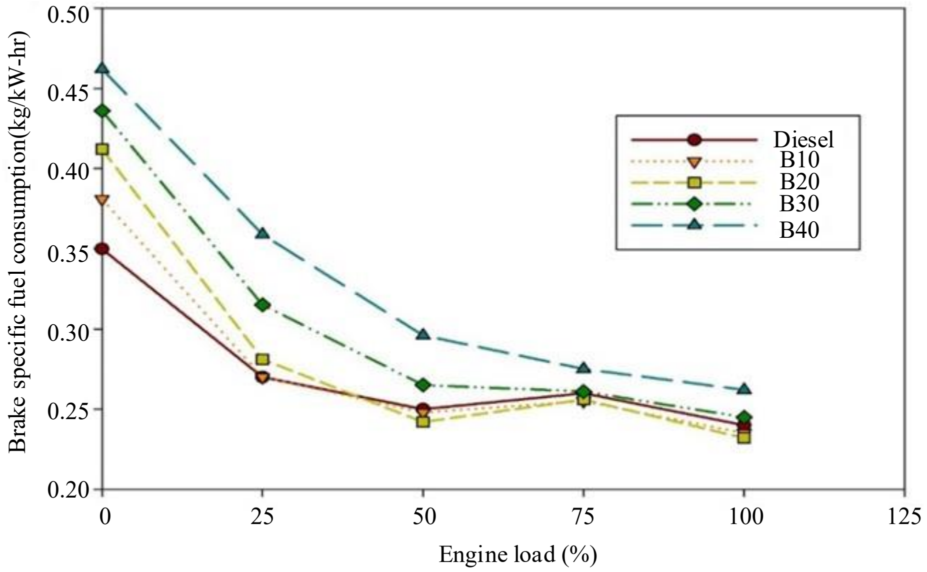

Figure 7. Brake specific fuel consumption Vs engine load.

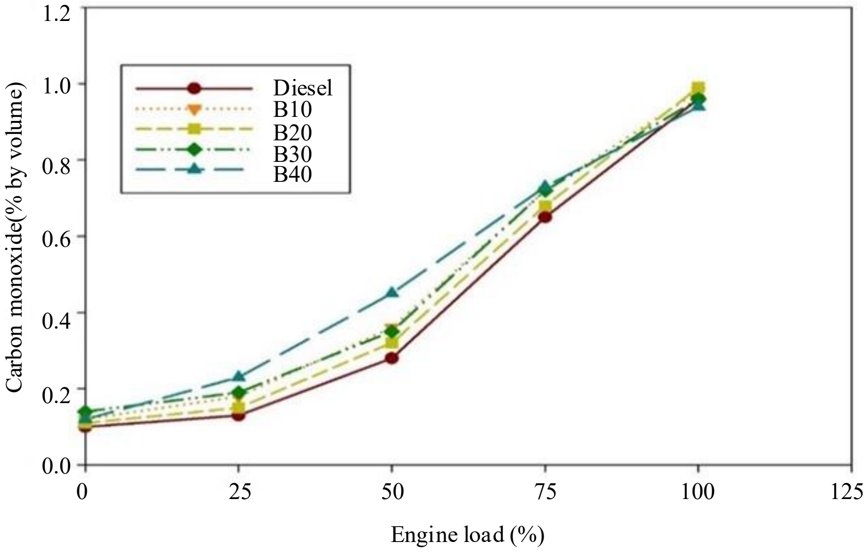

Figure 8. Carbon monoxide Vs engine load.

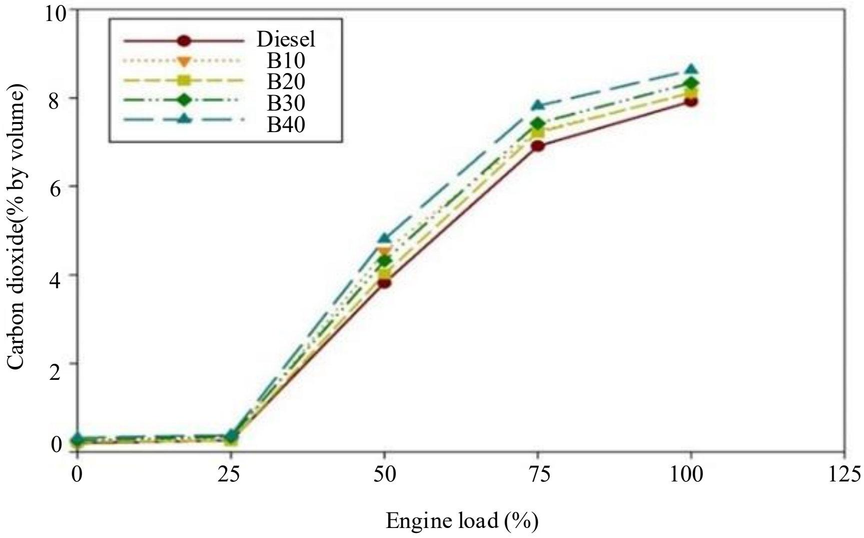

Figure 9. Carbon dioxide Vs engine load.

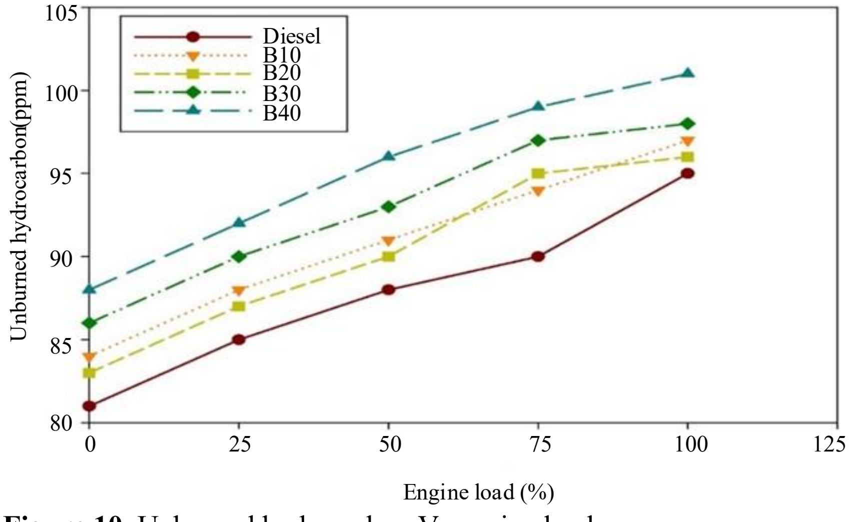

Figure 10. Unburned hydrocarbon Vs engine load.

Figure 10 shows that the amount of unburned hydrocarbons (HC) that come out of biodiesel increases as the biodiesel concentration goes up. This is mostly because the fuel and air don't mix as well and the biodiesel is less volatile. Diesel (D100) had the lowest quantity of hydrocarbons (95 ppm) at full load because it was quite volatile and had a low viscosity, which helped it atomise well and burn well. B20 gave off 96 ppm, which is only a small 1.05% increase, but its oxygen content (around 10–11 wt%) helps the flame spread. B30 and B40 had greater HC levels (98 ppm and 101 ppm, respectively) because they were thicker and didn't break up as well when sprayed, especially when it was cold. This caused incomplete combustion near the walls of the chamber. Biodiesel has oxygen in it, but higher blends need more advanced injection or heating tactics to keep HC emissions under control.

Figure 11 shows that NO_x emissions go up when the engine load is up because the peak temperatures are higher and the high-temperature residence durations are longer. At maximum load, diesel (D100) released 856 ppm, whereas B20 lowered NO_x to 853 ppm. This is because B20 has about 10–11 wt% oxygen, which helps combustion happen efficiently but in a controlled way. This steady release of heat lowers the number of hot patches that create thermal NO_x. B30 and B40, on the other hand, released 880 ppm and 900 ppm, respectively. This was because there was more oxygen available and the ignition was delayed, which made the premixed combustion phase stronger and boosted the flame temperatures. B20 kept NO_x levels similar to diesel across all loads. However, higher blends need more complicated controls like EGR or Split injection to lower their high NO_x levels, even if they burn more efficiently.

Figure 12 shows that FSN goes up when the engine load goes up because richer mixes and greater in-cylinder temperatures make soot develop. Diesel (D100) had the greatest FSN (6.2) at full load, while B20 lowered it to 6.0, a 3.2% decrease, since its oxygen concentration helped soot oxidation during diffusion combustion. B20's balanced viscosity (around 4.5 cSt) also helps with better atomisation and burning. B10 reduced smoke at lower loads, while B30 and B40 had FSNs of 6.1 and 6.25, respectively, since their higher viscosity and lower volatility made spray breakup worse and created more fuel-rich zones. So, B20 does the best job of stopping smoke, especially when the load is low or medium. This is because biodiesel's oxygen keeps soot from forming even when the temperature isn't ideal.

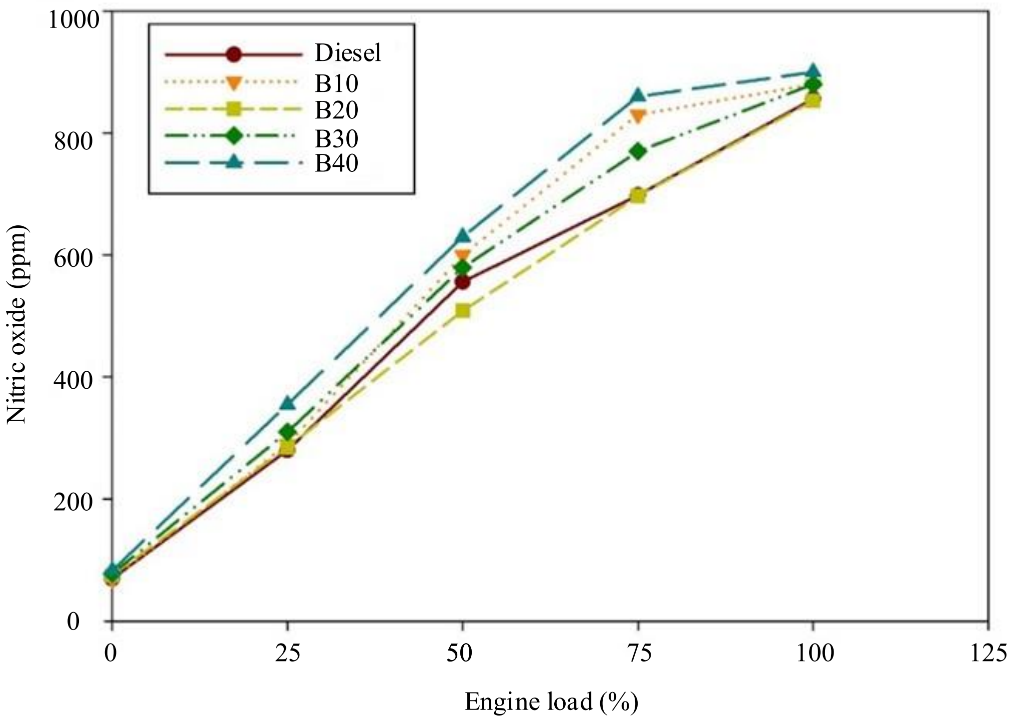

Figure 11. Nitric oxide Vs engine load

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

Combustion Analysis

Figure 13 shows that HRR changes with crank angle, which is a sign of how the gasoline burns. At 50° CA, diesel (D100) achieved 45 J/°CA, whereas B20 peaked at 49 J/°CA, which is nearly 9% higher. This means that premixed combustion happened faster and more efficiently because biodiesel has more oxygen, which helps mix the air and fuel better. B40 had the highest HRR (53 J/°CA), although this makes people worry about too much pressure in the cylinder and perhaps NO_x or mechanical stress. B30 and B40 also had longer combustion tails (25°–75° CA), which help the fuel burn but might potentially raise HC emissions and exhaust temperatures. B20, on the other hand, had a crisp, controlled HRR peak with a smooth decrease, which showed that it had good phasing, the best ignition delay, and stable combustion. Overall, B20 is the ideal fuel since it releases energy, burns efficiently, and controls emissions.

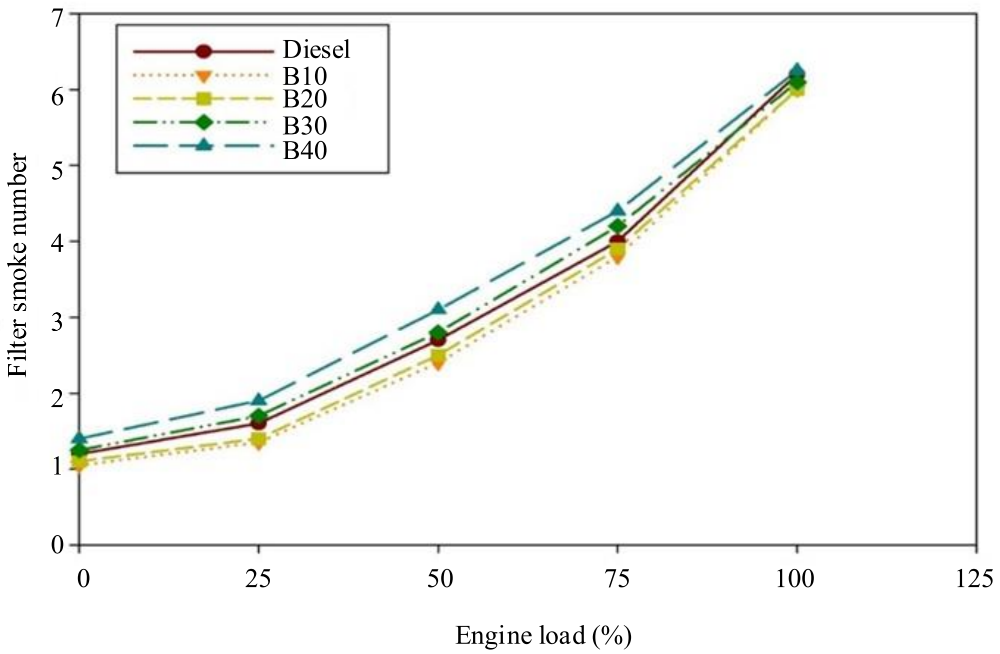

Figure 12. Filter smoke number Vs engine load

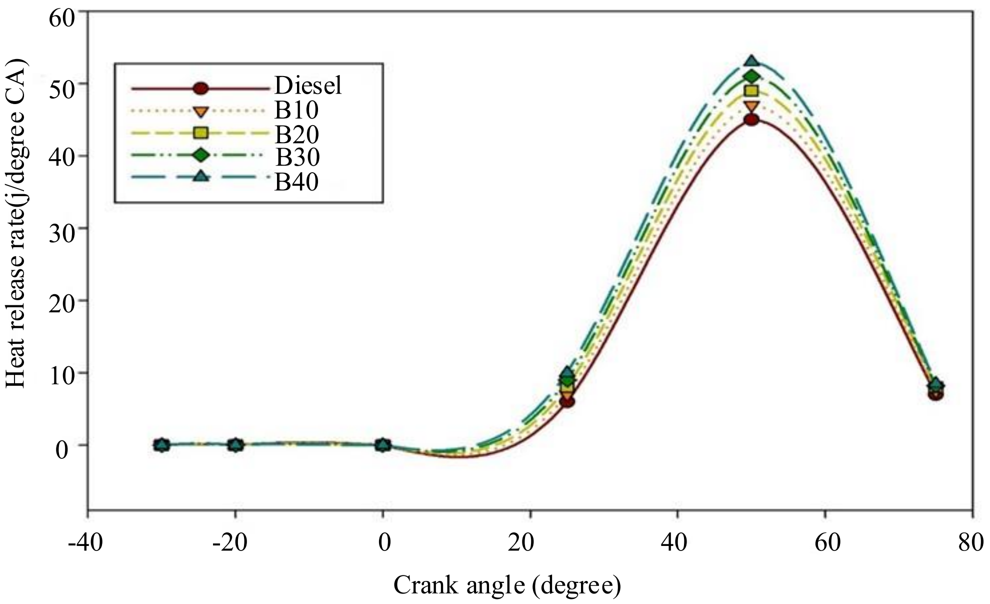

Figure 13. Heat release rate Vs crank angle.

Figure 14 shows that the peak cylinder pressure goes up with BMEP for all fuels because the combustion conditions get better. At full load (BMEP = 5 bar), diesel (D100) reached 65 bar, and B20 went a little higher, to 66 bar (1.5% higher), which means that the combustion was more complete and efficient. B20 has more oxygen and a higher cetane number, which make it easier to start and spread flames. B30 and B40 had somewhat higher pressures (66.2 and 66.5 bar), but their higher viscosity and lower volatility made atomisation worse, which caused combustion to be less even and emissions to be higher. On the other hand, B20 kept the best crank angle timing and pressure rise rates, which made the engine run more smoothly and safely. This made it the most thermodynamically efficient and balanced blend.

Figure 15 shows that ignition delay (ID) goes down as BMEP goes up for all fuels. This is because autoignition works better at higher temperatures and pressures. At full load, diesel (D100) had an ID of 13.8°CA, and B20 had an ID of 13.9°CA, which is almost the same. This shows that they burned in the same way. B20's high cetane number and oxygen content let radicals develop more quickly, which helps ignition happen quickly and reliably. B30 and B40 took a little longer (14.2°CA and 14.5°CA) because they were thicker and more complicated, which made it harder for the air and fuel to combine. Overall, B20 is the ideal choice since it keeps the good spray properties while improving the ignition chemistry. This leads to stable, efficient combustion with less chance of pressure spikes or banging.

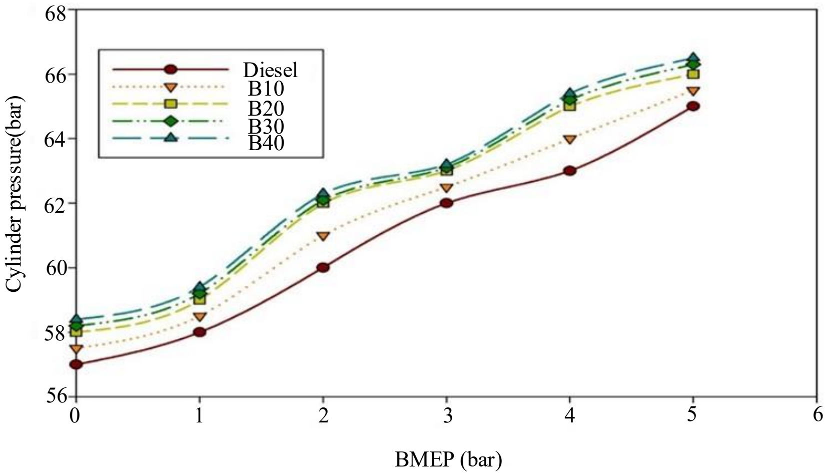

Figure 14. Cylinder pressure Vs BMEP.

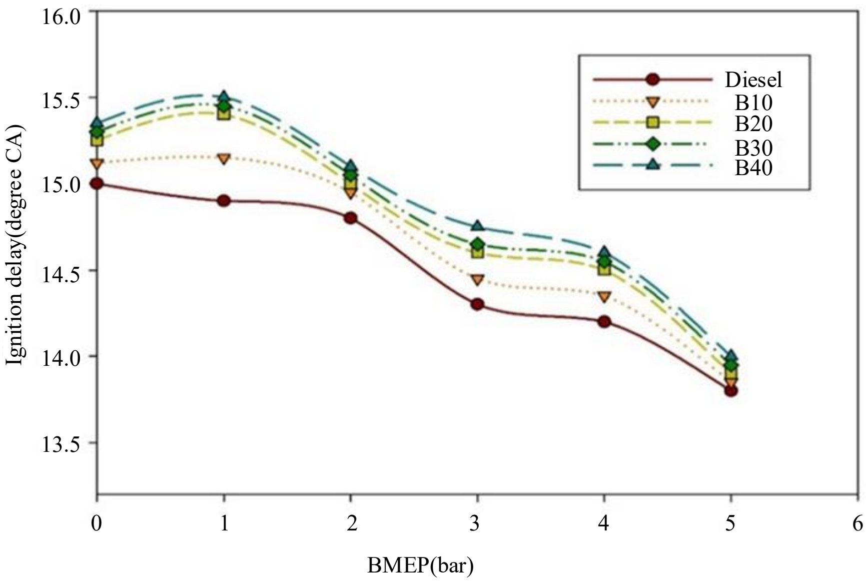

Figure 15. Ignition delay Vs BMEP.

While B30 and B40 exhibited slightly higher HRR peaks and cylinder pressures compared to B20, no abnormal combustion features such as pressure oscillations or knock-like phenomena were observed. The cyclic stability was verified by analyzing consecutive in-cylinder pressure cycles, where the coefficient of variation of IMEP remained below 5% for all blends, indicating stable operation. The pressure rise rates also stayed within safe limits, and the combustion traces showed smooth profiles without irregular spikes. Since the fuels were homogeneous diesel–biodiesel blends without water content, the risk of micro-explosions or secondary atomization was negligible. Therefore, the description of 'stable combustion' refers to low cyclic dispersion, controlled pressure rise, and absence of knock-like oscillations, even at higher biodiesel concentrations.

CONCLUSION

Among Chlorella vulgaris biodiesel blends, B20 emerged as the most effective for CI engines. It achieved a BTE of 27.89%, close to diesel's 30.12%, with the lowest BSFC (0.232 kg/kWh) and improved combustion due to higher oxygen content. Emission analysis showed minimal increases in CO and CO_2, stable HC levels, reduced smoke (FSN 6.0), and slightly lower NO_x (853 ppm) than diesel. Combustion analysis revealed better heat release and cylinder pressure, with ignition delay nearly matching diesel. Overall, B20 offers the best balance of efficiency, emissions, and combustion performance, making it a promising diesel alternative without engine modifications.

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