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Structure–Property–Performance Characteristics of Chlorella Vulgaris Lipid-Based Bio-Composites Modified with n-Pentanol

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Abstract

The depletion of fossil fuel resources and increasingly stringent emission regulations have intensified the need for sustainable alternatives for compression ignition (CI) engines. Biodiesel derived from Chlorella vulgaris microalgae is a renewable, non-edible fuel; however, its higher viscosity and lower volatility can adversely affect engine performance. To address these limitations, higher alcohols such as n-pentanol can be employed as effective modifiers to improve fuel physicochemical properties while maintaining compatibility with existing engines. In this study, diesel–biodiesel–n-pentanol lipid-based bio-composite fuels were experimentally investigated in a single-cylinder direct injection CI engine under varying load conditions. The test fuels included neat diesel (D100), B20, and B20 blended with 5–20% n-pentanol namely B20+75D5P (20% biodiesel, 75% diesel, and 5%n-pentanol), B20+70D10P (20% biodiesel, 70% diesel, and 10%n-pentanol), B20+65D15P (20% biodiesel, 65% diesel, and 15%n-pentanol), and B20+60D20P (20% biodiesel, 60% diesel, and 20% n-pentanol). Brake thermal efficiency increased with engine load for all fuels, with diesel achieving a maximum value of 30.12% at full load. The addition of n-pentanol resulted in slightly lower peak efficiency compared to diesel; however, significant emission improvements were observed. At full load, the B20+70D10P bio-composite reduced carbon monoxide emissions from 0.96% to 0.89% and unburned hydrocarbons from 95 to 75 ppm, while nitrogen oxide emissions remained comparable to diesel and smoke emissions were well controlled. Overall, B20+70D10P exhibited the most balanced structure–property–performance behavior, offering improved emission characteristics with acceptable engine performance.

Keywords: Bio-composite fuels, Lipid-based polymers, Chlorella vulgaris biodiesel, and n-Pentanol modifier.

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INTRODUCTION

The rapid consumption of fossil fuel reserves, coupled with the increasing stringency of global emission regulations, has led to a surge in research activities on sustainable and low-emission alternative fuels for compression ignition (CI) engines.

Conventional diesel engines are leading factors behind global warming and urban air pollution; hence, the need for renewable fuels that can be readily used without major engine refitting. Biodiesel is one of the most promising substitutes for diesel fuel due to its renewable nature, biodegradability, higher cetane number, and natural oxygen content, which have been demonstrated to play a significant role in CO, unburned HC, and particulate matter emission reduction [1], [4].

Besides, biodiesel can be mixed with petroleum diesel and used in current CI engines, thus representing a good short, term option for reducing emissions.

Even with these benefits, using biodiesel at higher blend ratios is limited by a number of disadvantages, viz. higher viscosity, lower calorific value, poorer cold flow properties, and a tendency to increase nitrogen oxide (NOx) emissions [3], [10]. These drawbacks have a negative impact on how fuel is atomized, the depth of the spray, and the efficiency of combustion, thus resulting in an increase in brake-specific fuel consumption and a decrease in engine performance. To overcome these issues, the idea of upgrading fuel by adding oxygenated additives has attracted a lot of attention as a very good solution for improving both fuel properties and combustion behaviour [2].

Among different oxygenated additives, higher alcohols have been shown to offer better performance than lower alcohols mainly because of their higher energy density, better miscibility, and lesser hygroscopicity. In particular, n-pentanol appears to be an excellent additive mainly because of its good physicochemical properties, such as a lower viscosity, a higher heating value than ethanol and butanol, and a better compatibility with diesel-biodiesel blends [8], [9]. A number of studies have indicated that n-pentanol addition leads to better spray atomization, increases air-fuel mixing, and results in more complete combustion, which in turn improves brake thermal efficiency and reduces CO, HC, and smoke emissions [10], [12], [14], [16]. Besides, ternary blending of diesel, biodiesel, and higher alcohols has been found to provide better combustion stability and emission control than binary blends [5], [6], [7], [11].

Recently, research has emphasized how selecting the right biodiesel feedstocks can be a key factor in improving sustainability further. In this context, microalgae, derived biodiesel, especially from Chlorella vulgaris, is being talked about more and more as a potential source because of its very high lipid productivity, fast growth, no competition with food crops, and excellent carbon sequestration capacity [1],[15].

Research work on Chlorella vulgaris biodiesel has confirmed that this biofuel presents a very good combustion performance and leads to lower emissions when blended with diesel fuel, more significantly when such blends are combined with fuel modification methods like alcohol addition or nano- additives [1], [16].

On the other hand, in spite of a great number of studies on biodiesel alcohol blends, there are still very few diesel-B20-n-pentanol blend studies being carried out over a broad range of engine load and speed [13].

Here, the main purpose of this study is to experimentally investigate the performance and emission characteristics of a changed fuel CI engine running on diesel-B20-n-pentanol ternary blends that are based on Chlorella vulgaris microalgae biodiesel. The role of n-pentanol in reducing the negative effects of biodiesel and improving the general engine behavior is also to be clarified by adjusting the n-pentanol concentration while keeping the biodiesel fraction fixed. This work contributes to a better understanding of diesel-biodiesel-pentanol blends as a sound choice of next-generation CI engine fuels.

In lipid-based bio-composite fuel systems, the compositional structure plays a decisive role in governing thermo-physical properties, which subsequently influence functional performance. The ester-rich molecular structure of Chlorella vulgaris biodiesel forms a polymer-like matrix, while n-pentanol acts as a molecular modifier that alters intermolecular interactions and volatility. These structural modifications translate into measurable changes in viscosity, combustion behaviour, and emission characteristics, establishing a clear structure–property–performance relationship.

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This work advances the current knowledge of algal-lipid-derived bio-composites in several important ways. First, very few studies have systematically characterized the structure–property–performance nexus of ternary diesel–B20–n-pentanol blends derived specifically from Chlorella vulgaris [17,18,19]. Second, by treating the lipid-ester matrix as a polymer-like composite system modified by a higher alcohol, this study introduces a composite-materials perspective into fuel science [20,21]. Third, it demonstrates simultaneous improvements in thermo-physical properties, combustion efficiency, and emission reduction — outcomes not previously reported together for this fuel system [22].

MATERIALS AND METHODS

The increasing demand for sustainable and eco-friendly energy resources has accelerated research into bio-based alternatives capable of replacing conventional diesel fuels without requiring engine modifications. Biodiesel derived from microalgae Chlorella vulgaris is a renewable and non-edible fuel source; however, its higher viscosity, lower volatility, and reduced calorific value limit direct application and adversely affect fuel handling and performance. To address these limitations, higher alcohols such as n-pentanol were employed as effective modifiers due to their favourable physicochemical properties, including improved volatility and better miscibility with biodiesel–diesel blends. In the present study, Chlorella vulgaris lipid-based bio-composites were formulated through volumetric blending of diesel, 20% biodiesel, and varying fractions of n-pentanol (≤20%) without altering engine hardware. The selected blend compositions were finalized based on fuel characterization and stability considerations, enabling systematic evaluation of structure–property–performance relationships under different operating conditions. This approach provides a practical framework for assessing the feasibility of n-pentanol-modified algal biodiesel blends as sustainable alternatives for future energy applications.

Biodiesel Production from Chlorella Vulgaris

The production of biodiesel started with the choice of the microalgal species Chlorella vulgaris (Figure 1), mainly because of its characteristics such as high lipid content, fast growth, and being a good candidate for biofuel production. Steps for producing biodiesel from the microalgae Chlorella vulgaris are shown in Figure 2. The microalgal strain chosen was grown in BG-11 medium in a photo bioreactor under controlled conditions, where the temperature was kept at 25°C, the pH was allowed to vary between 7. 0 and 7. 5, the light intensity was 2000-3000 lux, and the 16:8 h light-dark photoperiod was maintained. The supply of air with 2% CO_2 was continuously given to make photosynthetic efficiency and biomass productivity higher.

The algal biomass was collected by centrifugation at 5000 rpm for 10 min upon reaching the late exponential growth phase. After the biomass collection, it was washed off to remove nutrient residues and dried in an oven at 60°C until the weight became constant. Lipids were then extracted from the dried biomass using a chloroform-methanol solvent system (2:1 v/v). Figure 3 demonstrates the extracted crude algal oil which was separated and weighed to determine quantity.

The crude algal oil was then turned into biodiesel by alkali, catalyzed transesterification with a methanol- to- oil molar ratio of 6:1 and 0.5 - 1 wt.% NaOH catalyst at 60-65°C under continuous stirring. After the reaction was complete, the mixture was left to separate into phases, then washed with water and dried to get rid of the residual catalyst and impurities.

The purified algal biodiesel (fatty acid methyl esters), shown in Figure 4, was eventually utilized for fuel property characterization and engine performance and emission analysis.

Preparation of Diesel–Biodiesel–n-Pentanol Ternary Blends

The ternary fuel blends were a mix of commercial diesel, Chlorella vulgaris biodiesel, and analytical - grade n-pentanol. Based on volume, four blends were prepared: B20+75D5P (20% biodiesel, 75% diesel, and 5%n-pentanol), B20+70D10P (20% biodiesel, 70% diesel, and 10%n-pentanol), B20+65D15P (20% biodiesel, 65% diesel, and 15% n-pentanol), and B20+60D20P (20% biodiesel, 60% diesel, and 20% n-pentanol). The biodiesel was obtained through alkali-catalysed transesterification and its properties determined according to ASTM standards before mixing. A fixed 20% biodiesel blend was chosen because of its widely documented compatibility with standard diesel engines without the need for hardware modifications and at the same time it provides enough oxygen content to improve combustion efficiency and lower carbonaceous emissions.

Figure 1. Algae

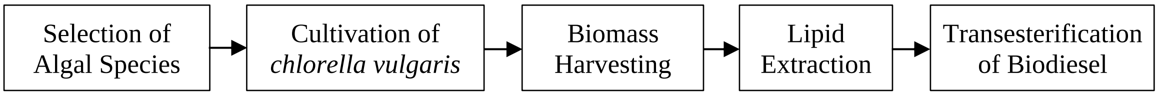

Figure 2. Steps of biodiesel production from Chlorella vulgaris microalgae

Figure 3. Raw Algae oil

Figure 4. Algae bio-diesel oil

The components were combined in measured amounts at room temperature (27°C) and the magnetic stirrer was operated at 800-1000 rpm for 30 minutes to get a thorough and uniform mixture.

The gradual increment of n-pentanol concentration from 5% to 20% was a way to thoroughly assess its effect on the fuel's physicochemical properties and combustion behavior.

Adding n-pentanol to the mix increases the total oxygen content and makes the blend more volatile because of its lower viscosity and higher latent heat of vaporization than biodiesel, thus, it helps spray atomization and air-fuel mixing in the CRDI engine. On the other hand, more alcohol content can lower the cetane number and calorific value, which may lead to an extended ignition delay.

The ternary ratios chosen were therefore aimed at striking a perfect balance between the ignition quality, combustion efficiency, and emission reduction.

The resulting blends were put in tightly sealed amber bottles and kept under observation for phase stability for 24 hours during which no separation was noticed. The stabilized fuels were then subjected to physicochemical characterization and detailed engine performance, combustion, and emission analysis.

n-Pentanol functions as a molecular-level plasticizer within the ester-rich composite matrix, disrupting intermolecular hydrogen bonding and depressing the effective glass transition temperature (Tg) of the system. This is consistent with the observed reductions in kinematic viscosity and pour point with increasing n-pentanol content [17,20].

The addition of n-pentanol reduces the overall polarity of the bio-composite fuel, decreasing its affinity for water uptake and improving moisture resistance. This is supported by improved cold-flow behavior and the absence of phase separation over 24 hours of storage [21,22].

Fuel Properties of Diesel–Biodiesel–n-Pentanol Blends

The physical and chemical properties of the diesel, B20, n-pentanol, and ternary blends shown in Table 1. changed regularly with the increasing fraction of n-pentanol.B20 had higher density (876 kg/m³) and viscosity (4. 76 cSt) than diesel (828 kg/m³, 2. 39 cSt) because of the oxygenated ester structure of biodiesel, which can negatively affect spray breakup in CRDI systems.

Adding n-pentanol gradually lowered the density from 862. 2 kg/m³ (5P) to 850. 5 kg/m³ (20P) and the viscosity from 3. 9 to 3. 1 cSt, thus making the fuel more flowable and easier to atomize.10P (3. 55 cSt) gave a perfect viscosity level that was still well within the ASTM D445 specifications for diesel fuels.

B20 had much higher flash and fire points (160°C and 170°C) than the other samples, which means that it was safer but less volatile. The addition of n-pentanol reduced these values, with 10P showing flash and fire points of 56°C and 63°C, respectively, which are comparable to diesel and fulfill ASTM D93 specifications, hence resulting in more evaporation and better air-fuel mixing.

The cold flow characteristics of the blend were significantly enhanced by pentanol addition; the cloud point was lowered from +5°C (B20) to −4°C (10P), and the pour point was improved to −13.5°C at 20P, meaning that the fuel can be used at lower temperatures.

The calorific value went down from diesel (42 MJ/kg) to B20 (39. 67 MJ/kg) and then very slightly as the pentanol fraction increased; nevertheless, 10P still had a fairly high heating value (40. 05 MJ/kg).

Cetane number decreased slowly with the addition of pentanol, but 10P still had a value of 52. 2, which was close to diesel (52) and met ASTM D613, thus providing good ignition quality.In general, 10P was the most harmonious blend in terms of volatility, viscosity, ignition quality, and energy content.

Table 1. Fuel properties of diesel, biodiesel, n-pentanol, and biodiesel blends.

Fuel Blend	Density (kg/m³)	Kinematic Viscosity (cSt)	Flash Point (°C)	Fire Point (°C)	Cloud Point (°C)	Pour Point (°C)	Calorific Value (MJ/kg)	Cetane Number
Diesel	828	2.39	46	52	0	−15	42	52
B20	876	4.76	160	170	5	−7	39.67	55.8
Pentanol	815	2.89	49	55	−32	−38	34.65	17
B20+75D5P	862.2	3.9	68	75	−2	−6	40.21	52.6
B20+70D10P	858.14	3.55	56	63	−4	−9	40.05	52.2
B20+65D15P	853.85	3.33	52	58	−5.8	−11.9	39.27	51.7
B20+60D20P	850.5	3.1	50	56	−6.5	−13.5	39	51.2

The reduction in density and viscosity with increasing n-pentanol content indicates modification of intermolecular interactions within the lipid-based composite matrix. Such structural modification improves volatility and spray characteristics, directly influencing combustion and performance behavior.

Experimental Engine Setup and Test Procedure

An experimental investigation has been done on a single- cylinder, four stroke, water-cooled, direct - injection compression ignition (CI) diesel engine at a fixed speed of 1500 rpm with a rated power of 3. 7 kW. A schematic diagram of the experimental test rig is illustrated in Figure 5. The engine had a bore of 87. 5 mm, a stroke of 110 mm, a displacement volume of 661. 45 cm³, a connecting rod length of 234 mm, and a compression ratio of 17. 5:1. The fuel was injected at an injection pressure of 200 bar and the injection timing of 23° before top dead centre (bTDC).

The experimental setup included measuring the intake air flow rate by means of a differential air flow sensor. At the same time, fuel consumption measurement was done using a calibrated burette. Through the usage of chromium-alumel (K-type) thermocouples, the temperatures of the exhaust gas, cooling water, and the ambient were constantly monitored. Besides, the cooling water flow rate measurement was done with a rotameter. The engine load was controlled by an eddy current dynamometer.

Exhaust emissions from the vehicle in terms of carbon monoxide (CO), carbon dioxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx), were measured using an AVL Digas 444 five, gas analyzer. At the same time, filter smoke number was determined by means of an AVL 415SE smoke meter.

Table 2. Abbreviations used in the experimental setup

Abbreviation	Description	Abbreviation	Description	Abbreviation	Description
FT1–FT2	Flow Transducers	SM	Smoke Meter	CI	Compression Ignition Engine
FMB	Fuel Measuring Burette	EGC	Exhaust Gas Calorimeter	ECD	Eddy Current Dynamometer
DMM	Digital Manometer	FIP	Fuel Injection Pump	CAE	Dynamometer Controller and Analyzer
EGA	Exhaust Gas Analyzer	PP	Pressure Pickup	CA	Combustion Analyzer

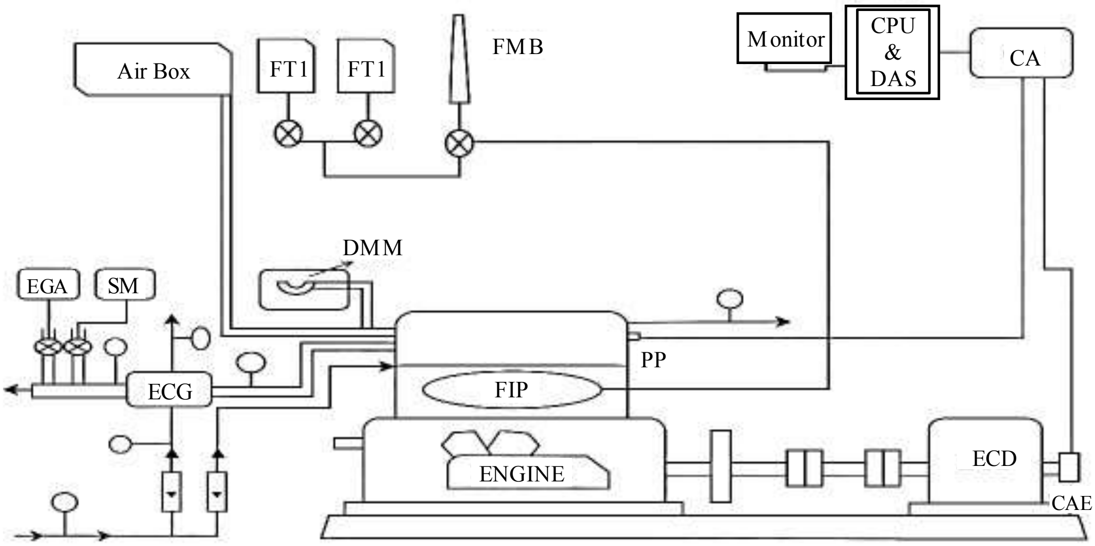

Figure 5. Engine Setup

A computerized data acquisition system was connected to the test engine to record performance, combustion and emission parameters. The diesel engine was run using biodiesel-diesel-alcohol blends (B20+75D5P, B20+70D10P, B20+65D15P and B20+60D20P) under various load conditions.

RESULTS AND DISCUSSION

In this section, a thorough evaluation of the performance and emission characteristics of a compression ignition engine fueled with diesel-B20-n-pentanol ternary blends is made.The effect of different n-pentanol levels on the performance parameters such as brake thermal efficiency and brake specific fuel consumption has been investigated at different engine load conditions.

Furthermore, the paper discusses exhaust emission characteristics which include carbon monoxide (CO), carbon dioxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx) and filter smoke number (FSN). These features are scrutinized and compared to those of neat diesel fuel and the B20 blend.

The findings are evaluated to determine how effective the addition of n-pentanol is in improving engine performance and cutting down on harmful emissions. Thus, the study presents the potential of diesel-biodiesel-n-pentanol blends as a sustainable source of fuel for compression ignition engine operations.

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

Figure 6 illustrates Brake thermal efficiency (BTE) that continued to rise with increasing engine load for all the tested fuels. At maximum load, diesel (D100) registered the highest BTE of 30. 12%, whereas B20 had a lower figure (27. 89%, 7. 4% drop) because of its lower energy content and higher viscosity. The use of n- pentanol led to an increase in BTE, and B20+65D15P was the top performer among blends (28%), merely 7. 0% lower than diesel and 0. 4% higher than B20.

The observed changes in engine performance can be directly correlated with the optimized thermo-physical properties resulting from molecular-level modification of the lipid-based bio-composite structure.

Figure 7 illustrates that Brake specific fuel consumption (BSFC) decreased with increasing engine load for all fuels. At full load, diesel exhibited an SFC of 0.24 kg kW/h, while B20 showed a slightly lower value (0.23 kg kW/h). The addition of n-pentanol significantly reduced SFC, with B20+75D5P and B20+70D10P achieving the lowest values (0.20 kg kW/h), corresponding to a 16–17% reduction compared to diesel. Higher pentanol fractions (15–20%) resulted in increased SFC due to the lower calorific value of the blends. Overall, B20+70D10P emerged as the optimum blend, offering the lowest and most consistent fuel consumption relative to diesel and B20.

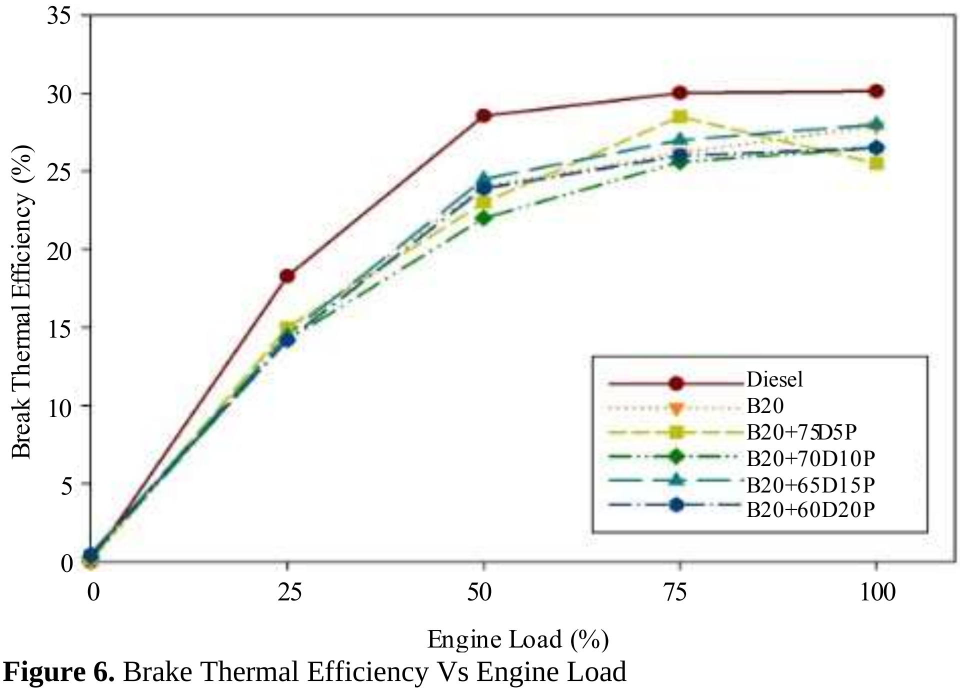

Figure 6. Brake Thermal Efficiency Vs Engine Load

Emission Analysis

Figure 8 illustrates the trend of CO emissions rising with load for all the tested fuels. At full load, diesel gave out a 0. 96% CO, whereas B20 showed a marginal rise (0. 99%).The n-pentanol addition brought about a remarkable drop in CO emission, and B20+75D5P was the only one reaching such a low CO level (0. 82%), equivalent to a 14. 6% reduction in comparison with diesel, which was caused by the combustion of raised oxygen content and the volatility improvement. A higher n-pentanol content (20%) brought about an increase in CO emissions because of a longer ignition delay. In general, B20+75D5P has been recognized as the best mixture for reducing CO emissions in comparison with diesel.

The oxygenated structure of the lipid–alcohol bio-composite promotes improved oxidation and more homogeneous combustion, confirming the structure–property–performance interdependence of the fuel system.

Figure 9 illustrates that CO_2 emissions rose with the engine load for all types of fuels. CO_2 emissions from diesel at full load were 7. 9%, whereas B20 showed only a slight increase (8. 1%).The use of n, pentanol brought about a decrease in the amount of CO_2 released, and B20+75D5P was the blend with the lowest CO_2 emissions (7. 2%), which is about 8. 9% less than diesel, because of its lower carbon content and more oxygenated combustion.

Higher percentages of n-pentanol had the effect of slightly increasing CO_2 emissions as a consequence of ignition delay impacts. Therefore, B20+75D5P was the blend that was the most efficient in reducing CO emissions compared to diesel.

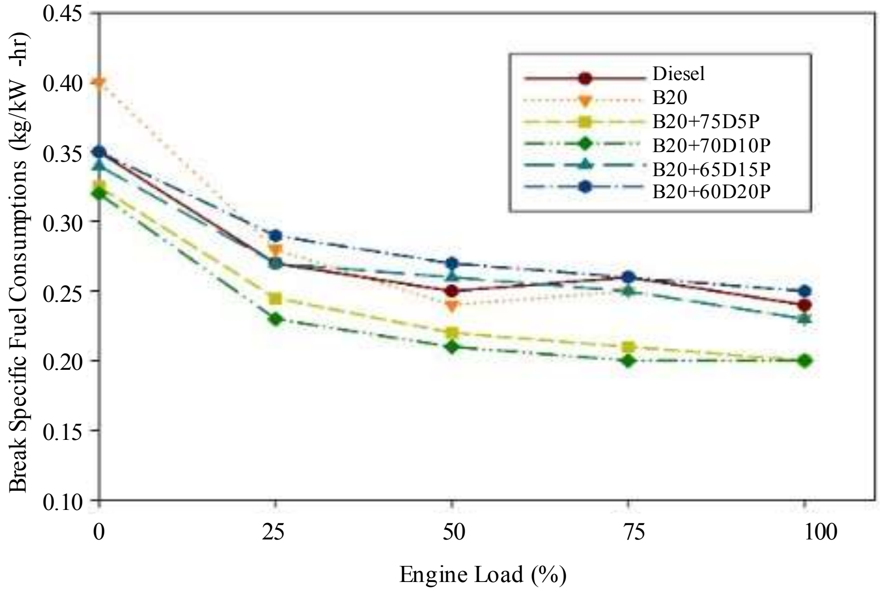

Figure 7. Brake Specific Fuel Consumption Vs Engine Load

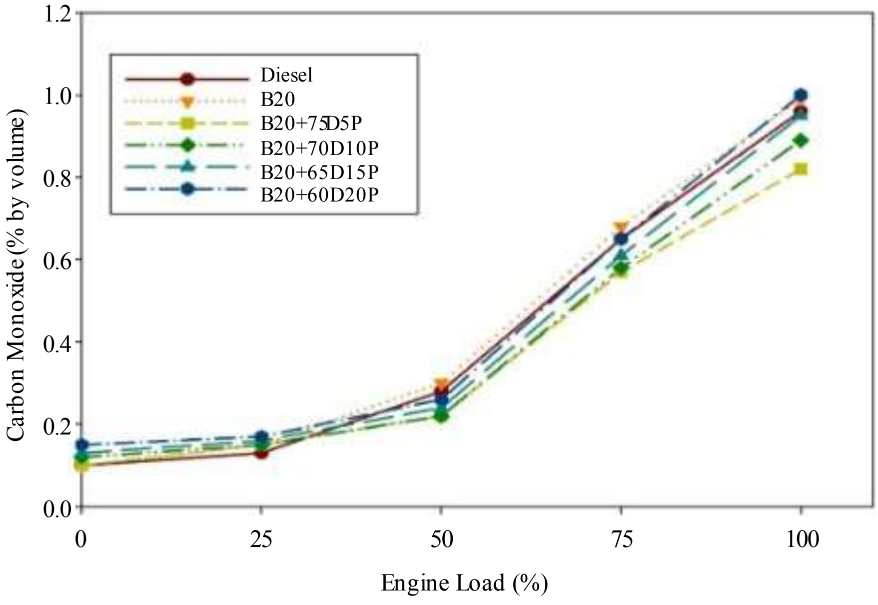

Figure 8. Carbon Monoxide Vs Engine Load

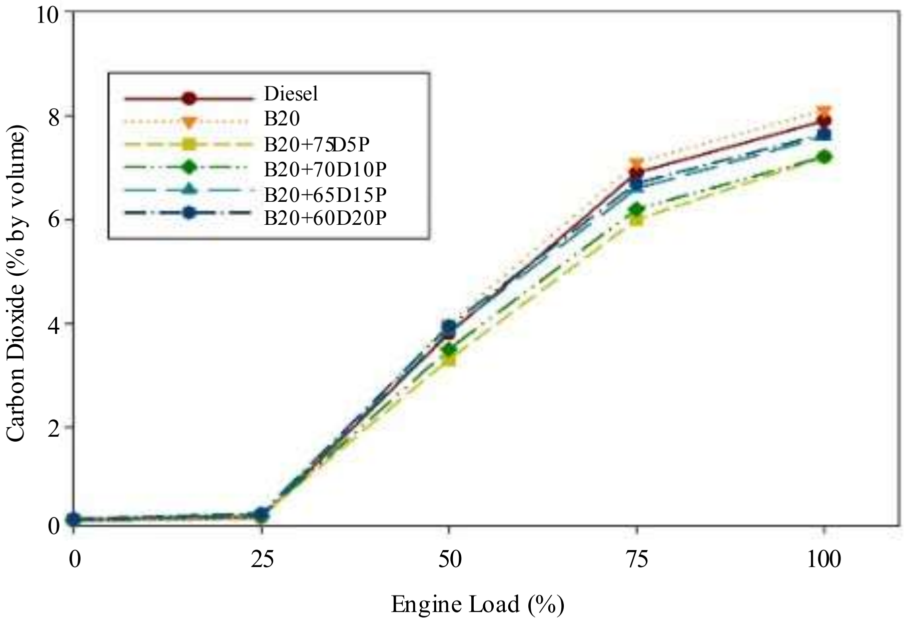

Figure 9. Carbon Dioxide Vs Engine Load

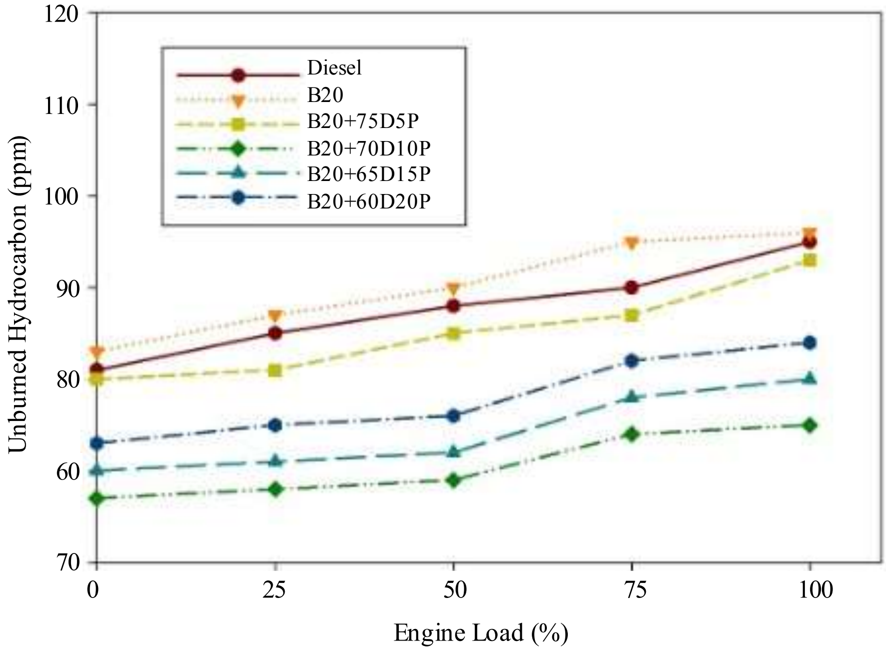

Figure 10. Unburned Hydrocarbons Vs Engine Load

Figure 10 reveals that the HC emissions increased as the engine load was increased for all the fuels. At the maximum load, diesel released 95 ppm, whereas B20 registered a marginally higher figure (96 ppm). The incorporation of n-pentanol significantly brought down the HC emissions, with B20+70D10P registering the minimum HC concentration (75 ppm), which is 21% less than that of diesel, owing to better oxygenated combustion and increased volatility. The blends with higher pentanol fractions gave relatively higher HC because of the ignition delay effect. Therefore, B20+70D10P was the HC emission reduction blend from diesel.

Figure 11 illustrates the variation of NOx emissions with engine load for different fuels. At full load, diesel emitted 856 ppm, whereas B20 was almost the same (857 ppm). The use of n-pentanol contributed

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to changes in NOx production, B20+70D10P having the lowest NOx emission (850 ppm), which is equivalent to a 0. 7% decrease from diesel, as a result of a lower peak combustion temperature. A greater amount of n-pentanol drastically increased NOx due to ignition delay premixed combustion. Therefore, B20+70D10P was considered the best blend in terms of NOx abatement compared to diesel.

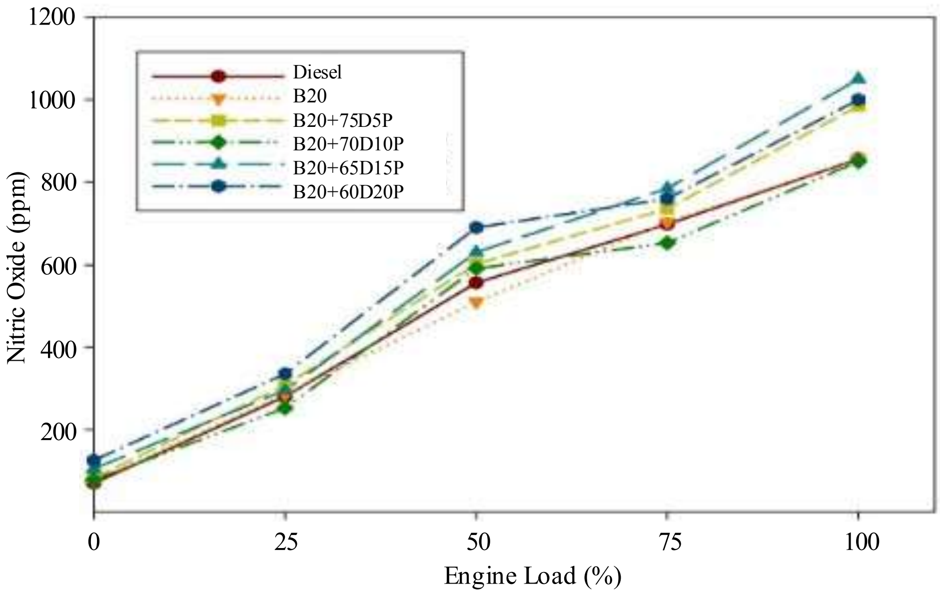

Figure 11. Nitric Oxide Vs Engine Load

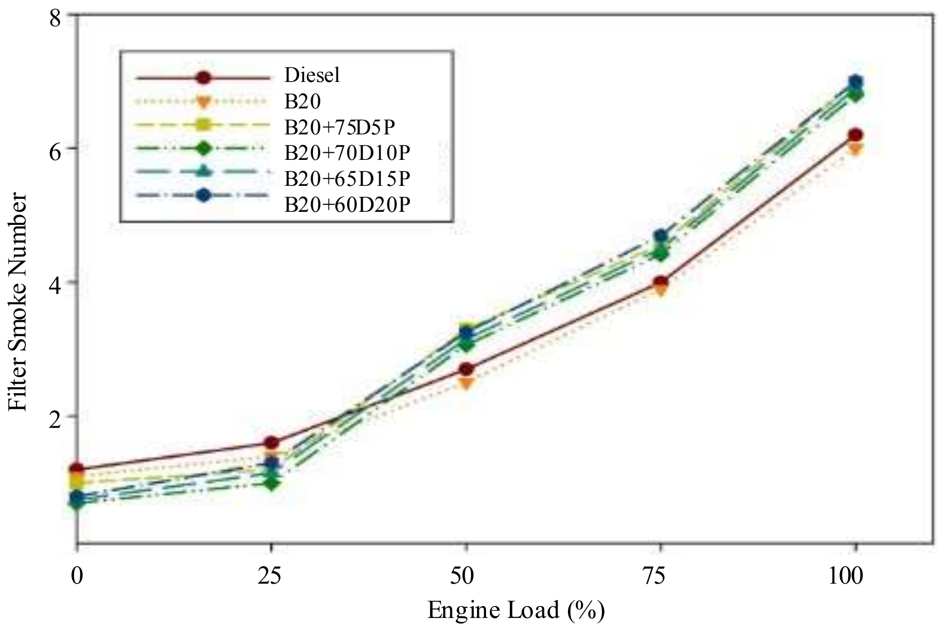

Figure 12. Filter Smoke Number Vs Engine Load

Figure 12 illustrates that the Filter smoke number(FSN) increased with engine load for all fuels. At full load, diesel recorded an FSN of 6.2, while B20 showed a slightly lower value (6.0) due to improved soot oxidation. The addition of n-pentanol significantly reduced smoke at low and medium loads, with B20+70D10P exhibiting the lowest FSN values (0.7 at no load and 1.0 at 25% load). Higher n-pentanol fractions (15–20%) increased FSN at high loads due to prolonged ignition delay and locally rich zones. Overall, B20+70D10P emerged as the optimum blend, offering effective smoke reduction across a wide load range compared to diesel and B20.

CONCLUSION

The results of the experimental study revealed the trend that brake thermal efficiency (BTE) goes up with engine load for all the tested fuels, and diesel attained the maximum efficiency of 30. 12% at the full load. The B20 mixture was less efficient than diesel because of the lower calorific value as well as higher viscosity of the former. The addition of n- pentanol enhanced the volatility of the fuel and the preparation of the mixture, thus resulting in a level of performance roughly equal to B20 and close to diesel. At full load, B20+70D10P brought down CO emissions to 0. 89% from 0. 96% (diesel) and 0. 99% (B20), and HC emissions to 75 ppm from 95 ppm (diesel) and 96 ppm (B20). NOx emissions by B20+70D10P (850 ppm) were similar to diesel (856 ppm), and smoke opacity was well controlled. In summary, B20+70D10P was found to be the best blend that gave a good balance between engine performance and emission reduction without the need for engine modification.

Overall, the study establishes a clear structure–property–performance relationship in Chlorella vulgaris lipid-based bio-composites, where controlled n-pentanol modification optimizes thermo-physical properties and enhances functional performance.

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