Journal of Mines, Metals and Fuels, *72(5): 499-507; 2024. DOI: 10.18311/jmmf/2024/45188*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.com/index.php/jmmf*

A Comprehensive Study on *Calophyllum inophyllum* Biodiesel and Dimethyl Carbonate Blends: Performance Optimization and Emission Control in Diesel Engines

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Abstract

The rising fuel demand, driven by expanding logistical infrastructure, transportation sector growth, and the need for faster transport modes, has led to significant urban sprawl and vehicle emissions, posing serious threats to air quality and human health. Chronic exposure to vehicle emissions is linked to severe health issues such as lung cancer, asthma, cardio-respiratory problems, hypersensitivity, and hypertension. In response, the quest for alternative fuels from renewable resources, particularly biodiesel, has gained momentum. Biodiesel, derived from waste seed oil, animal fat, and vegetable oil, presents a promising substitute for traditional diesel fuel. This study investigates the effects of bl enhances diesel with up to 20% Dimethyl Carbonate (DMC), an oxygenated additive, to enhance ignition properties. Engine performance and emissions were assessed under standard operational conditions. Results indicated that pure biodiesel achieved a maximum cylinder pressure 1.73% higher than diesel. Increasing DMC content in the biodiesel blend resulted in a 21.54% higher Heat Release Rate (HRR) and a 17.75% improvement in brake thermal efficiency compared to pure biodiesel at higher loads. However, the higher DMC blend also increased NOx emissions by 4.2% while significantly reducing smoke, hydrocarbon (HC), and carbon monoxide (CO) emissions by 32.5%, 36.36%, and 35.65% respectively, compared to diesel at maximum load.

Keywords: *Biodiesel, Calophyllum inophyllum, Dimethyl Carbonate, Emissions*

1.0 Introduction

The stringent emission regulations adopted by the government, such as the BS-IV norms (equivalent to Euro 6 standards in developed countries), aim to minimize automobile emissions. This, along with an impending

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fuel crisis, has driven the search for alternative fuel sources. Many nations rely heavily on petroleum fuels for agricultural machinery and transportation, while a few countries dominate petroleum production, causing price fluctuations and supply uncertainties for others. India, for example, imports about two-thirds of its petroleum, significantly impacting the environment and human health due to emissions from these fuels Elangovan *et al*[1]. Kurniati *et al*[2]. Kedia A.G[3] explains dimethyl carbonate as a cost-effective substitute of methanol for biodiesel production via transesterification of nonedible oil. In this context, biomass has emerged as a promising renewable energy source; particularly as traditional energy sources like petroleum, coal, and natural gas become depleted. Biomass can be converted into liquid and gaseous biofuels through thermochemical or biological processes Jahirul *et al*[4]. In recent years, biodiesel has gained importance due to its biodegradability, renewability, and environmental benefits[5]. Unlike petroleum fuels, biodiesel from vegetable oils contains 10-45 % oxygen by mass, which enhances combustion efficiency. Additionally, biodiesel has low sulfur and nitrogen content, making it more environmentally friendly. The focus on biodiesel in developing countries has increased, contributing to economic growth, especially in rural areas. Biodiesel, a renewable and biodegradable fatty acid methyl ester, can be produced from various vegetable oils and animal fats. However, using edible oils for fuel is impractical due to their high cost and demand for food purposes. Therefore, research has shifted towards non-edible oil crops, which are promising sources of alternative fuels[6,7]. Biodiesel can be used in diesel engines without modifications and can be blended with petroleum diesel in any proportion, offering higher flash points, improved cetane numbers, and reduced harmful emissions and investigated the physicochemical properties of biodiesel blends with petro-diesel, finding that these blends meet ASTM standards and enhance fuel atomization and combustion. India has successfully used biodiesel from Jatropha, which has shown superior performance characteristics and reduced emissions compared to conventional diesel, though with slightly higher NOx emissions. India produces approximately 6.73 million tons of non-edible oils annually from sources such as linseed, castor, karanji, neem, Palash, and Kusum, with significant production potential. This study focuses on biodiesel from *Calophyllum inophyllum oil*, evaluating its properties and suitability for use in existing diesel engines without major modifications[8]. The main challenge with Calophyllum Oil Biodiesel (COB) is its oxidation stability. Ashok *et al*[9]. explored the effects of metal oxide nanoparticles like zinc oxide, titanium dioxide, and antioxidants like ethanox, finding that while ethanox reduces NOx emissions, it increases CO, HC, and smoke emissions[10]. *Calophyllum inophyllum*, known as the Beauty leaf tree, is a large evergreen tree widely available in India, Australia, and East Asia. It is commonly cultivated in tropical regions and tolerates various soil types, including coastal sand, clay, and degraded soils. In India, it is found in the Andaman and Nicobar Islands, Lakshadweep, Karnataka, Kerala, Odisha, Maharashtra, and Tamil Nadu, with an average oil yield of 11.7 kg per tree, or 4680 kg per hectare, second only to palm oil. While biodiesel combustion produces lower emissions of HC, CO, CO_2, smoke, particulate matter, and polycyclic aromatic hydrocarbons, the excess oxygen in biodiesel leads to increased NOx formation. Techniques like Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR) are commonly used to reduce NOx emissions. EGR recirculates a portion of exhaust gas back into the combustion chamber, lowering oxygen concentration and combustion temperature, while SCR uses ammonia to convert NOx into nitrogen, water, and CO_2. Ashok *et al.*[11] found that adding higher alcohols like n-pentanol and n-octanol to Calophyllum Oil Biodiesel reduces NOx and HC emissions, although it increases smoke and CO emissions. Fuel emulsification, which involves mixing fuel with water, is an effective method to reduce NOx, particulate matter, and smoke emissions. The micro-explosion phenomenon during combustion enhances fuel atomization and combustion efficiency, leading to lower adiabatic flame temperatures and reduced NOx formation[12]. Additionally, emulsified fuel increases engine output power due to the expansion of water vapors during combustion. The literature review indicates several methods for reducing NOx emissions, each with its drawbacks. Adding antioxidants reduces NOx emissions but concurrently increases CO, HC, and smoke emissions. Blending with higher alcohols reduces NOx and HC emissions but leads to higher levels of CO and smoke emissions. Limited research has been conducted on the inclusion of water in Calophyllum Oil Biodiesel. This study focuses on a 10% water-COB blend aimed at lowering combustion temperatures. Water inclusion in biodiesel promotes complete combustion, thereby reducing CO and HC emissions. Anant *et al*[13-16]. discussed material selections and Computational Fluid Dynamics (CFD) approaches for thermal cooling, while Shital *et al*[17-19] provided critical reviews on heat transfer enhancement in heat exchangers. Rahul Khot *et al*[20-24] investigated laser welding parameters on the strength of TRIP steel. Manzoore elahi m *et al*[25] explains comprehensive review on biodiesel, nanofluid, and the role of artificial intelligence and machine learning. Biradar, R.G[26] explains use of nahar biodiesel and its blends as an alternative fuel in CI diesel engine.

The present study focuses on enhancing heat transfer using wavy corrugated twisted tape inserts. Biodiesel, derived from renewable sources like vegetable oils and animal fats, offers a more sustainable and environmentally friendly alternative to traditional diesel. Its compatibility with existing engines and superior lubricating properties improves performance and engine longevity. Biodiesel also supports local economies, reduces dependence on imported oil, and benefits from government incentives, making it a viable alternative fuel. Adding Dimethyl Carbonate (DMC) to biodiesel blends enhances oxygen content, improving combustion efficiency and reducing emissions of pollutants such as carbon monoxide and unburned hydrocarbons. DMC increases the cetane number for better ignition and smoother engine performance, improves cold flow properties for use in colder climates, and acts as a solvent for a homogeneous blend with traditional diesel. Furthermore, DMC's biodegradable and less toxic nature aligns with environmental goals of reducing the ecological footprint of fuels. It. analyzes engine performance and emissions using WIC and compares them with neat diesel. The research highlights the impact of varying percentage of *Calophyllum inophyllum* biodiesel and dimethyl carbonate blends under standard engine operating performance and findings were compared with those obtained using pure diesel. The higher amount of oxygen in the dimethyl carbonate blend improved the efficiency of the combustion process and reduced the amount of smoke capacity and other pollutants. The experiments are conducted using B-100, B-50, B-50 + DMC-10, B-50 + DMC-15 and B-50 + DMC-20.

2.0 Experimentation

Experiments were conducted on a Kirloskar-manufactured engine, as depicted in Figures 1 and 2. A rope brake dynamometer was employed for loading. The specifications of the 4-stroke diesel engine used in these experiments are detailed in Table 1. Prior to commencing the experimental investigation, several preliminary checks were carried out: ensuring the availability of a water source for the engine jacket inlet and calorimeter, verifying proper electrical connections, confirming an adequate level of lubricating oil, and ensuring no air was trapped in the fuel line. Before starting the engine, it was also confirmed that there was no load on the weight hanger. Once the engine was started, the correct flow of fuel into the pump and through the nozzle into the engine cylinder was ensured. After the engine stabilized at no-load condition speed, the time taken for 10 cc of fuel consumption was recorded. Subsequently, the necessary dead weights were applied. At each load step, the engine speed from the RPM indicator, the fuel rate from the burette, and the spring balance readings were recorded from the panel instruments. Analyzing the exhaust emissions was a significant task, performed using an exhaust gas analyzer positioned at the exhaust manifold of the engine. The experiments were conducted using various fuel blends: B-100, B-50, B-50 + DMC-10, B-50 + DMC-15, and B-50 + DMC-20.

2.1 Chemical and Physical Properties

- Chemical Formula: $C_3H_6O_3$.
- Molecular Weight: 90.08 g/mol.
- Appearance: Colorless, clear liquid.
- Odor: Mild, pleasant odor.
- Density: 1.069 g/cm^3 at 20°C.
- Boiling Point: 90°C (194°F).
- Melting Point: 2-4°C (36-39°F).
- Flash Point: 18°C (64°F) (closed cup).
- Solubility: Miscible with most organic solvents; slightly soluble in water.
- Vapor Pressure: 42 mmHg at 20°C.
- Viscosity: 0.664 cP at 25°C.

2.1.1 Chemical Properties

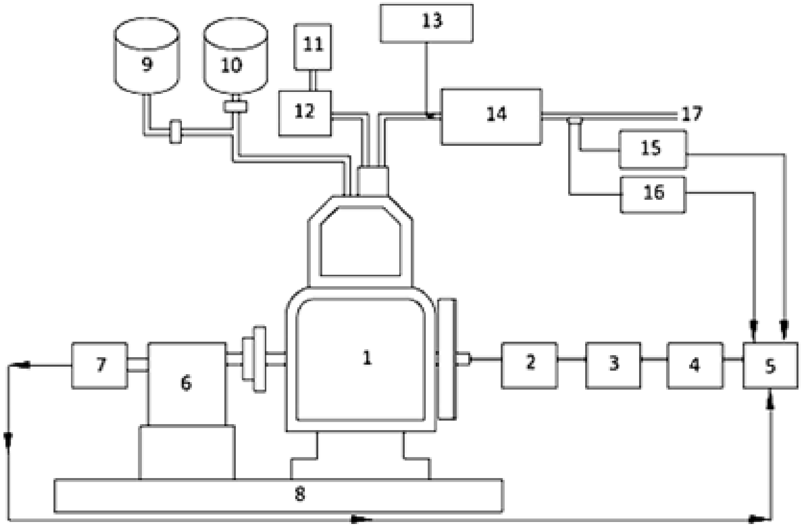
- Reactivity: Stable under normal conditions, but can react with strong acids and bases.
- Flammability: Flammable liquid and vapor.
- Autoignition Temperature: 458°C (856°F).
- Partition Coefficient (log P): 0.23.

3.0 Results and Discussions

3.1 Performance Analysis

3.1.1 Brake Thermal Efficiency

Brake Thermal Efficiency (BTE) is a key performance metric for internal combustion engines, including diesel



(1) Kirloskar engine. (2) Pressure transducer. (3) Charge amplifier. (4) Data acquisition system. (5) Computer. (6) Eddy current dynamometer. (7) Dynamometer control. (8) Test bed. (9) Diesel tank. (10) GSBD tank. (11) Air box. (12) Orifice. (13) Aqueous urea + injector (pump + ECU). (14) Cu zeolite SCR unit. (15) Five gas analyzer. (16) Smoke meter. (17) Tail pipe

Figure 1. Experimental setup

Table 1. Kirloskar single cylinder 4-stroke CI engine specifications

Specifications	Value
Compression Ratio	16.5:1
Method of Starting	Hand starting
Bore × Stroke (mm)	80 × 110
Cubic Capacity	624 cc
Maximum Power	5 HP
Nominal Speed	1500 rpm
Cooling System	Water cooled
Type of Loading	Mechanical loading
Type of Dynamometer	Rope brake dynamometer
Diameter of Brake Drum	37 cm
Spring Balance Indicator	0-20 kg

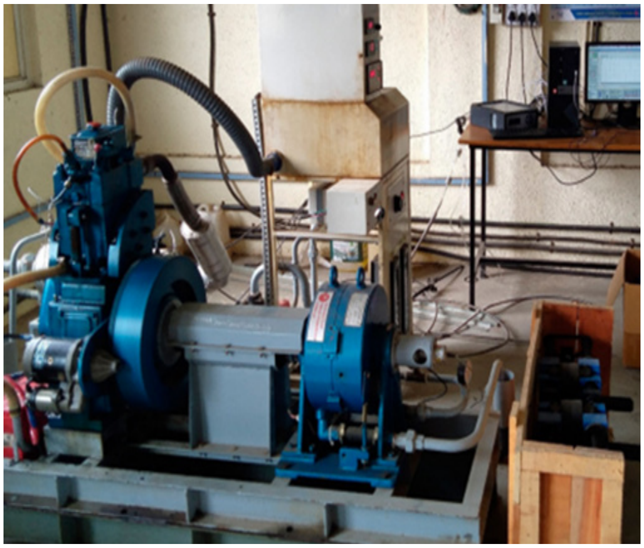


Figure 2. Actual setup.

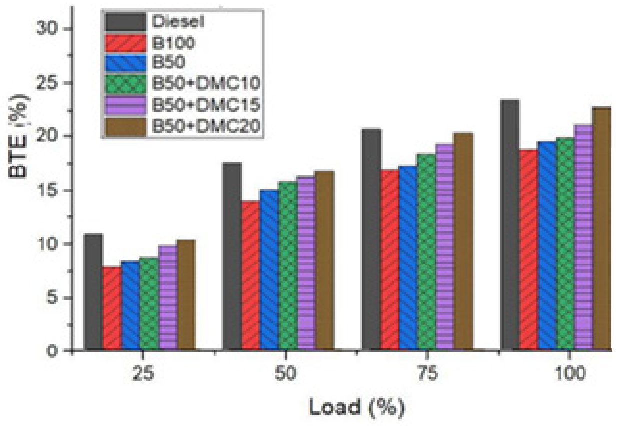


Figure 3. BTE vs load.

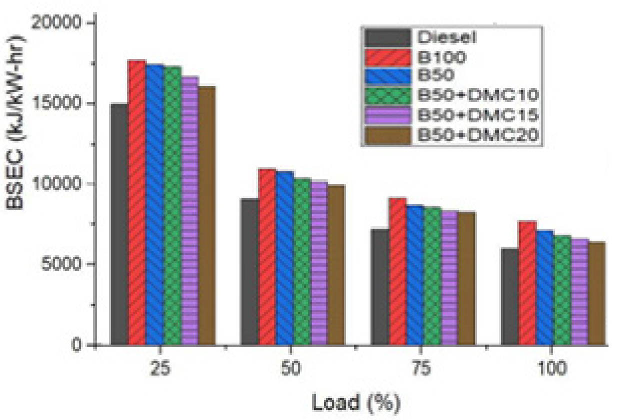


Figure 4. Bsec vs load.

engines. It measures the efficiency with which the engine converts the fuel's chemical energy into mechanical energy to produce useful work at the crankshaft. BTE is expressed as a percentage. Figure 3 explained that the BTE has improved with load for all combinations. Increasing load refers to having more fuel to cylinder, which results into more apparent combustion, generating, more heat and improving BTE. BTE changes from 17.82 to 32.22 %, 12.26 to 26.97 %, 14.94 to 27.80 %, 13.37 to 28.27 %, 16.56 to 29.60 % and 17.19 to 31.58 % for diesel, B-100, B-50, B-50 + DMC-10, B-50 + DMC-15 and B-50 + DMC-20. The BTE has increased by using DMC blends compared to pure diesel because DMC blends have higher calorific value and good atomization abilities.

3.1.2 Brake Specific-Energy Consumption

Brake Specific Energy Consumption (BSEC) is a measure of the energy efficiency of an engine or powertrain system. It represents the amount of energy consumed per unit of brake power produced by the engine. It is the energy produced inside the combustion chamber during burning a particular fuel. The lesser amount of BTE will have a greater BSEC. Figure 4 shows BSEC decreasing with increasing load. It varies from 20774.56 to 10530.28 KJ/KW-hr, 23885.27 to 12446.36 KJ/KW-hr, 23583.37 to 11812.96 KJ/KW-hr, 23434.16 to 11464.13 KJ/KW-hr, 22717.92 to 11227.90 KJ/KW-hr and 22091.95 to 11005.09 KJ/KW-hr for diesel, B-100, B-50, B-50 + DMC-10, B-50 + DMC-15 and B-50 + DMC-20. The blend B-50 + DMC-20 produces. It has a lower BSEC compared to other mixtures due to the inclusion of DMC, which accelerates combustion.

3.1.3 Brake Specific Fuel Consumption

Brake Specific Fuel Consumption (BSFC) is a measure of the fuel efficiency of an engine or powertrain system. It represents the amount of fuel consumed per unit of power produced by the engine. A critical performance metric used to gauge the effectiveness of diesel engines is BSFC. Fuel density, volumetric fuel injection, fuel viscosity and calorific value are the main factors affecting BSFC. The relationship between BSFC and BTE is inverse. The variation of BSFC concerning load is explained in Figure 5. It shows that BSFC reduces when the engine load increases, except for biodiesel. Additionally, the BSFC increases when the DMC is blended with biodiesel blend related to neat diesel fuel. This might be attributed to the claiming impact of DMC, which is caused by its higher latent heat of evaporation compared to diesel and biodiesel.

3.2 Emission Characteristics

3.2.1 Oxides of nitrogen emission

Oxides of nitrogen (NOx) emissions are a significant environmental and public health concern. NOx is a collective term for nitrogen monoxide (NO) and nitrogen dioxide (NO_2), which are produced during combustion processes, especially at high temperatures. These pollutants have various adverse effects, including

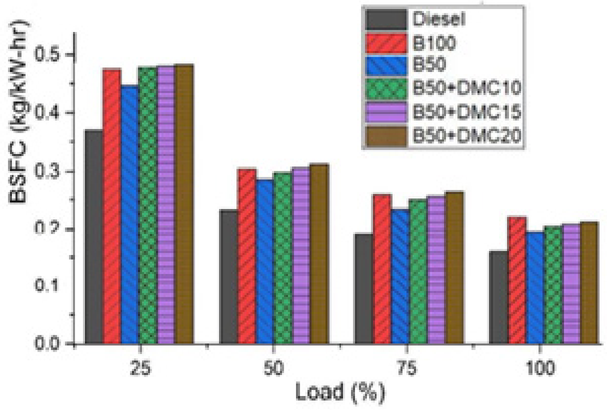


Figure 5. BSFC vs load.

contributing to air pollution, forming smog and acid rain, and causing respiratory problems.

Internal combustion engines in vehicles are a major source of NOx due to the high-temperature combustion of fuel. Figure 6 illustrates the changes in NOx emissions for the tested fuel. The NOx emissions for diesel, B-100, B-50, B-50 + DMC-10, B-50 + DMC-15 and B-50 + DMC-20 are 66 to 1638 ppm, 106-1652 ppm, 89-1665 ppm, 115-1663 ppm, 141-1693 ppm and 176-1807 ppm. The lower volatility of biodiesel results in a slower evaporation process compared to diesel fuel, and the lack of aromatic chemicals may contribute to the reduction in NOx emissions. At higher loads, B-50 + DMC-20 generates 4.3% more NOx emissions than diesel. Due to increased fuel consumption in the premixed combustion area and faster ignition from the higher oxygen content of DMC, the B-50 + DMC-20 blend improved BTE by 17.75% compared to biodiesel at higher loads.

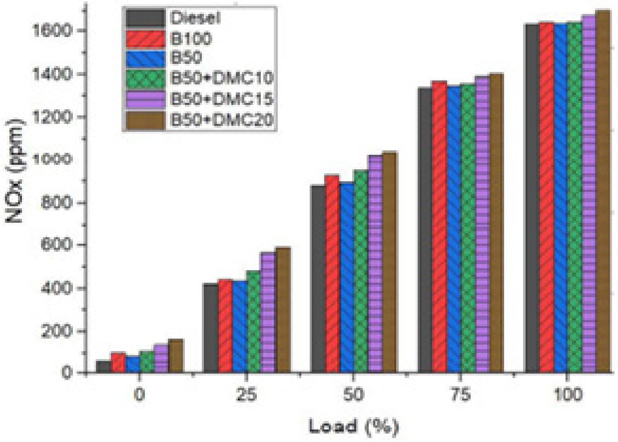


Figure 6. NOX vs load.

3.2.2 Smoke Opacity

Smoke opacity is a measure of the density or thickness of smoke emitted from combustion processes, such as those in engines, power plants, or industrial facilities. It is an indicator of the concentration of particulate matter in the exhaust gases. Smoke opacity is typically expressed as a percentage, with higher values indicating denser and more visible smoke.

Smoke opacity is influenced by oxygen deficiency, fuel atomization, incomplete combustion, and self-ignition temperature. Figure 7 demonstrates that the smoke opacity of the tested fuel is related to engine load. The smoke opacity for diesel, B-100, B-50, B-50 + DMC-10, B-50 + DMC-15 and B-50 + DMC-20 are 20.6-83.7 %, 15.6-78.2 %, 18.5-79.3 %, 10.1-67.8 %, 8.6-59.8 % and 7.3-56.3 %. For all test fuels, increasing the load resulted in higher smoke emissions. The smoke opacity of the blends was consistently lower than that of diesel at all loads, although it increased with higher engine load. Diesel fuel showed increased smoke emissions due to more fuel being injected into the cylinder. At higher loads, the B-50 + DMC-20 blend produced 32.5% less smoke opacity than diesel.

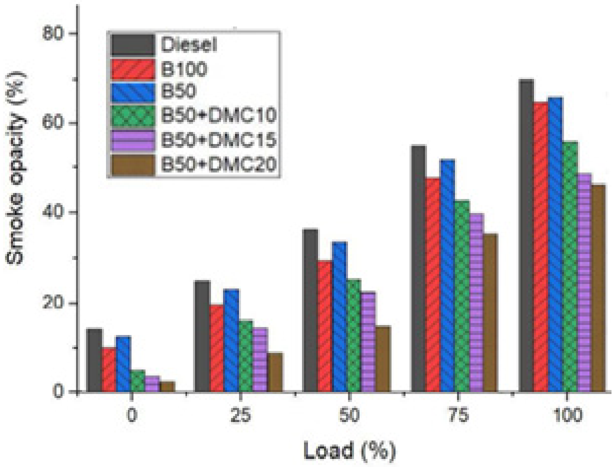


Figure 7. Smoke opacity vs load.

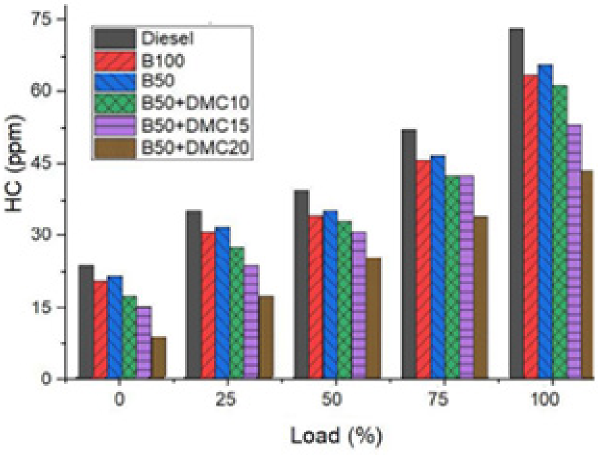


Figure 8. HC vs Load.

3.2.3 Hydrocarbon Emission

Hydrocarbon emissions refer to the release of unburned or partially burned fuel molecules (hydrocarbons) into the atmosphere. These emissions are typically the result of incomplete combustion in engines or other combustion processes. Hydrocarbons are a significant component of air pollution and contribute to the formation of ground-level ozone and smog. Figure 8 shows the variations in hydrocarbon emissions for the tested fuels. It was observed that hydrocarbon emissions increased across all blends with higher loads, due to the formation of a richer mixture. The HC emissions differ from 31-77 ppm, 28-68 ppm, 29-70 ppm, 25-66 ppm, 23-58 ppm and 17-49 ppm for diesel, B-100, B-50, B-50 + DMC-10, B-50 + DMC-15 and B-50 + DMC-20. The B-50 blend resulted in higher HC emissions compared to B-100, due to the oxygen present in the biofuel molecule. The HC emission of 37.36 % decreased in DME blends.

4.0 Conclusions

This study thoroughly examined the combustion, performance, and emission characteristics of a CRDI engine fueled with *Calophyllum inophyllum* biodiesel and its blend with dimethyl carbonate (DMC). Key findings reveal that adding DMC significantly impacts engine behavior. Enhanced combustion efficiency was observed due to the increased oxygen content in DMC, which raised in-cylinder temperature, accelerated ignition, and created a more substantial flame front, increasing the Mass Fraction Burned (MFB). The B-50 + DMC-20 blend reduced Mean Gas Temperature (MGT) through a cooling effect, sharply lowering gas temperature due to its high oxygen content. However, DMC addition resulted in a longer ignition delay period, attributed to a decrease in cetane number and increased latent heat of vaporization. Peak cylinder pressure with biodiesel was 1.73% greater than neat diesel, and the blend with higher DMC content demonstrated a 20.54% increase in heat release compared to diesel. The Brake Thermal Efficiency (BTE) of the blend was 17.75% higher than pure biodiesel, though still lower than diesel. Additionally, DMC significantly decreased smoke opacity by 20% and Hydrocarbon (HC) emissions by 31.5%. However, adding DMC to biodiesel blends slightly increased NOx emissions due to its high oxygen content, which enhances combustion but also raises temperatures, leading to more NOx formation. In conclusion, incorporating DMC into *Calophyllum inophyllum* biodiesel blends enhances combustion efficiency and reduces several harmful emissions, albeit with a slight increase in NOx emissions. These findings highlight the potential benefits and trade-offs of using DMC as an additive in biodiesel blends, offering valuable insights for optimizing biodiesel formulations for better engine performance and reduced environmental impact.

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