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Research Article

Investigation on performance and emission studies of variable compression ratio engine using neem oil biodiesel

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ABSTRACT

Biodiesel, particularly Neem oil-based biodiesel, has emerged as a promising eco-friendly alternative, offering reduced greenhouse gas emissions, lower sulphur content, cleaner combustion, and biodegradability. Variable Compression Ratio (VCR) engines further enhance performance, fuel efficiency, and emissions reduction across various fuels. This study focuses on experimenting with Neem-based biodiesel in VCR engines and conducting a parametric study to address the challenges of fossil fuel use. The experimental study revealed several key findings. CO emissions decreased with higher biodiesel blending and compression ratios, achieving a 28% reduction with NB50 at 6 N-m load and CR 22. CO_2 emissions are reduced by 20% using B40 at CR 22 under full load (12 N-m). A 27% reduction in HC emissions is noted with B30 at CR 20 under full load. NOx emissions increased by 20% at full load and CR 22:1 with pure diesel. Brake Thermal Efficiency increased by 16% with NB30 at 6 N-m load and CR 22. SFC significantly decreased under no-load conditions with NB50.Optimal results from AI-TLBO with NB40 fuel and a compression ratio of 22 at no-load showed reductions of 20.20% in CO, 23.84% in CO2, 24.5% in HC, and a 23.1% NOx increase.

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INTRODUCTION

The growing reliance on fossil fuels, particularly in the transportation sector, poses serious challenges due to their finite availability and detrimental environmental effects. Transportation, which consumes the largest share of petroleum, contributes significantly to pollution, adversely impacting the climate, human health, ecosystems, and agricultural productivity [1]. Fossil fuel combustion, especially in diesel engines used for maritime, rail, and road transport, produces harmful emissions such as carbon monoxide (CO), hydrocarbons (HC), sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM) [2, 3]. These pollutants not only exacerbate global warming but also degrade air quality, leading to severe health problems. Diesel engines, a critical component of internal combustion (IC) technology, are widely favored for their higher efficiency and durability compared to gasoline engines.

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However, the trade-off lies in their production of more pollutants. In addition to greenhouse gases like carbon dioxide (CO_2), diesel engines emit greater amounts of harmful pollutants [4]. This makes it imperative to explore alternative fuels that are cleaner and sustainable. India, like many countries, began addressing pollution with regulations in 1989, focusing on idle emission controls, followed by the introduction of mass emission standards in 1992 for diesel vehicles. However, despite regulatory advances, diesel engines continue to emit pollutants that harm both the environment and human health [5]. The need for cleaner fuel alternatives is pressing, particularly given the transportation sector's dominant role in petroleum consumption.

Research has shown that biodiesel, a renewable alternative to conventional diesel, offers significant advantages in reducing emissions. While biodiesel usage tends to increase NOx emissions, it can be controlled through exhaust gas recirculation (EGR) systems [6]. notably, biodiesel significantly reduces emissions of CO, PM, and HC, pollutants that are major contributors to air pollution. The U.S. Environmental Protection Agency (EPA) has acknowledged biodiesel's overall benefits, citing improvements in exhaust emissions except for NOx [7]. As fossil fuels become increasingly scarce and expensive; biofuels emerge as a practical and environmentally friendly alternative [8]. Fossil fuel combustion not only depletes natural resources but also accelerates environmental degradation, making the transition to alternative fuels essential. Though gasoline-based fuels remain viable in some regions, their availability is declining. Biofuels, produced from locally sourced materials, offer a promising solution to the ongoing energy crisis by providing a renewable and sustainable energy source [9].

One particularly promising biofuel is neem oil, which has been highlighted as an alternative biodiesel due to its lower viscosity and abundant availability [10]. Neem oil biodiesel, especially when blended with other biodiesel types, can significantly reduce emissions without compromising engine performance. With increasing energy demands and the dwindling supply of fossil fuels, research into renewable fuel sources like neem oil is accelerating. The key benefits of neem oil biodiesel include renewability, biodegradability, and improved exhaust emissions, making it a cost-effective and sustainable replacement for conventional diesel in compression ignition (CI) engines [11]. In addition to neem oil, researchers are exploring various organic additives that can enhance engine efficiency and reduce emissions. These additives improve combustion rates, lower exhaust emissions, increase mileage, and enable fuels to function under extreme temperatures. By integrating these additives into diesel fuels, engine performance and environmental impact can be optimized. Organic additives, with their higher oxygen content, contribute to better combustion, which in turn reduces harmful emissions. Several studies have compared the performance and emissions of different biodiesel blends with conventional diesel. For example, a study investigating biodiesel blends produced from rapeseed oil demonstrated reductions in CO and smoke emissions by up to 60%. Similarly, blends containing 20% and 40% biodiesel showed a reduction in NOx emissions by 39% and 28%, respectively, compared to standard diesel [12]. These findings underscore biodiesel's potential as a superior substitute for conventional diesel, particularly in reducing harmful emissions.

Further research into biodiesel production and engine performance has led to promising results. For instance, studies using Jetropha methyl ester (JTME) and diesel blends showed that JTME and its blends emit less heat and have lower emissions compared to diesel, with the exception of NOx. Other research involving marine diesel engines demonstrated that biodiesel blends with up to 50% biodiesel reduced emissions of PM, NOx, and CO. Experiments with ethanol as an additive in diesel fuel have also shown potential. Ethanol boosts fuel combustion, reducing CO_2 emissions by approximately 25% [13]. This model encourages increased biofuel use and offers a practical way to enhance the efficiency of gasoline engines. Additionally, experiments with microalgae biodiesel, produced via the transesterification technique, revealed improved performance and lower exhaust emissions when compared to conventional diesel. Researchers have also examined the effects of various engine parameters, such as fuel injection pressure and nozzle design, on biodiesel combustion. For example, studies showed that using higher fuel injection pressures improved engine performance and reduced emissions. Moreover, adjusting nozzle holes and compression ratios in diesel engines running on biodiesel blends has demonstrated significant improvements in efficiency and emission reductions [14].

In conclusion, the shift from fossil fuels to biodiesel and other renewable fuels is becoming increasingly critical due to the environmental and economic pressures associated with fossil fuel use. Biodiesel, particularly neem oil-based and other biofuel blends, presents a sustainable and eco-friendly alternative to conventional diesel, offering significant reductions in harmful emissions without compromising engine performance. Continued research and innovation in biodiesel production, engine optimization, and fuel additives will be essential in ensuring a cleaner and more sustainable energy future. Till date, no research has been found on high blending ratios with neem oil, nor on adjusting engine parameters, such as compression ratio, to accommodate these higher blends within the scope of literature review referred for the current study. Therefore, this study examines a higher compression ratio range of 14:1 to 22:1, an area still in need of exploration. Bio Diesel will be compulsory used in Marine Engine as a primary fuel. Current study will help to use biodiesel in Marine Engines. This study offers environmental and health benefits. By reducing greenhouse gas emissions, lowering sulfur content, and enabling cleaner combustion, biodiesel as a blending agent minimizes air pollution, which directly impacts respiratory health. Additionally, biodiesel's biodegradable nature lessens environmental contamination, making it a sustainable alternative to fossil fuels and contributing to a cleaner, healthier environment.

Emissions

Gasoline and diesel engine exhaust emissions are major contributors to atmospheric pollution, which has led to the development of alternative fuels [15]. Automobiles significantly contribute to this pollution by releasing harmful exhaust pollutants into the air, many of which are irritants, odorous, and even carcinogenic. Carbon monoxide (CO) emissions result from incomplete combustion, uneven air-fuel mixtures, and elevated chamber temperatures. Heavy-duty vehicles, particularly during start-up or acceleration under load, produce CO due to the higher fuel mixture used. The release of CO is not only wasteful in terms of fuel but also represents a loss of chemical energy.

Nitrogen oxides (NOx) are formed in the ignition chamber when oxygen and high temperatures are present. The reaction of NOx with natural gases creates ozone, a key component of photochemical smog. Prolonged exposure to NOx can lead to health issues such as cyanosis—especially on the lips, body, and toes—and can cause structural damage to lung cells [16]. Biodiesel has emerged as a popular alternative to fossil fuels, addressing both energy needs and concerns over global warming. As an environmentally friendly fuel, biodiesel helps reduce the carbon dioxide (CO_2) problem, which is a leading cause of global warming. This is because the CO_2 emitted during biodiesel combustion is equivalent to the amount absorbed by plants during their growth, thus avoiding the greenhouse effect [17]. Studies have shown the benefits of using biodiesel. For instance, Chen He et al. conducted experiments using cotton seed oil and diesel, finding that O_2 acts as an oxygen-donating catalyst, improving combustion and engine thermal efficiency. This catalyst also helps reduce emissions of CO and hydrocarbons. Neem oil and cotton seed oil, which contain 30% to 40% oil, are promising substitutes for other bio fuels [18]. Research by Md. Nurun Nabi et al. demonstrated that 76% of biodiesel can be recovered from cotton seed oil, with the remaining 23% consisting of methanol and other compounds. Similarly, neem oil biodiesel has been shown to enhance engine efficiency and reduce NOx emissions. In an experiment with cotton seed biodiesel, Sandeep Singh et al. suggested that 10%, 20%, and 30% biodiesel blends could serve as effective replacements for mineral oil diesel, offering properties similar to conventional diesel fuel [19].

MATERIALS AND METHODS

In this research, neem oil-based biodiesel was blended with diesel and evaluated for performance and emissions. The blends were assessed using an AVL Engine test rig, with emissions data collected via a smoke analyzer attached to the system. To reduce viscosity, neem oil sourced from a local market was transesterified. This process involved using a hot plate and magnetic sterner, with the raw neem oil preheated to 100°C to eliminate moisture. Sulfuric acid (H_2SO_4) was used for acid pre-treatment to lower the free fatty acid (FFA) content.

The performance and emission characteristics of neem oil blends (10%, 20%, 30%, 40%, and 50%) were compared to those of diesel. These blends, designated as NB10, NB20, NB30, NB40, and NB50, were prepared as shown in Figures 1. The engine's performance was tested under various loads with these biodiesel blends, and the results are discussed in subsequent sections. The properties of neem oil are presented in Table 1.

Figure 1. Biodiesel preparation setup.

Table 1. Properties of neem oil

Sample/ properties	Density at 30 °C	Calorific value	Calorific value	Flash point	Fire point	Kinematic viscosity @40 °C	Dynamic viscosity @40 °C
Unit	**Kg/m³**	**Cal/gm**	**Cal/gm**	**°C**	**°C**	**cSt**	**cP**
ASTM standard	D287	D4809	D4809	D9358T	D9258T	D445	D445
Std Diesel	816	10235	10841	53	56	2.09	1.73
NB10	824	10172	10758	62	66	2.35	1.93
NB20	833	10013	10599	69	74	2.66	2.21
NB30	839	9828	10414	76	82	2.86	2.39
NB40	846	9632	10218	81	85	2.93	2.48
NB50	861	8871	9457	121	136	4.4	3.8

EXPERIMENTAL WORK

The experiments were carried out under varying loads of 0, 3, 6, 9, and 12 kW at a constant rated speed, with an injection pressure of 210 bars and an exit cooling water temperature of 65°C. Five neem oil blends—NB10, NB20, NB30, NB40, and NB50—were tested. During each measurement, the engine was allowed to stabilize sufficiently. All readings were taken three times to ensure accurate and consistent results. The study evaluated performance parameters such as Mechanical Efficiency and Brake Thermal Efficiency, as well as emission parameters including Carbon Dioxide (CO_2), Carbon Monoxide (CO), Smoke, and Nitrogen Oxides (NOx). These results were compared to those of pure diesel. Prior to data collection, the engine was run for about three minutes to reach stability and maintain a constant speed of 1500 rpm. After the warm-up period, engine performance and emission measurements were recorded under different compression ratios of 14, 16, 18, 20, and 22.

Figure 2 shows the line diagram of the experimental setup used in the present study. Following are the notations used in the Figure 2.

T1 - Inlet (engine) water temperature (°C),
T2 -Outlet (engine) water temperature (°C),
T3 -Inlet (calorimeter) water temperature (°C),
T4 -Outlet (calorimeter) water temperature (°C),
T5 -Exhaust gas temperature before calorimeter (°C),
T6 -Exhaust gas temperature after calorimeter (°C),
F1 - Fuel consumption measurement unit,
F2 -Air flow measurement,
EGA -Exhaust gas analyzer and

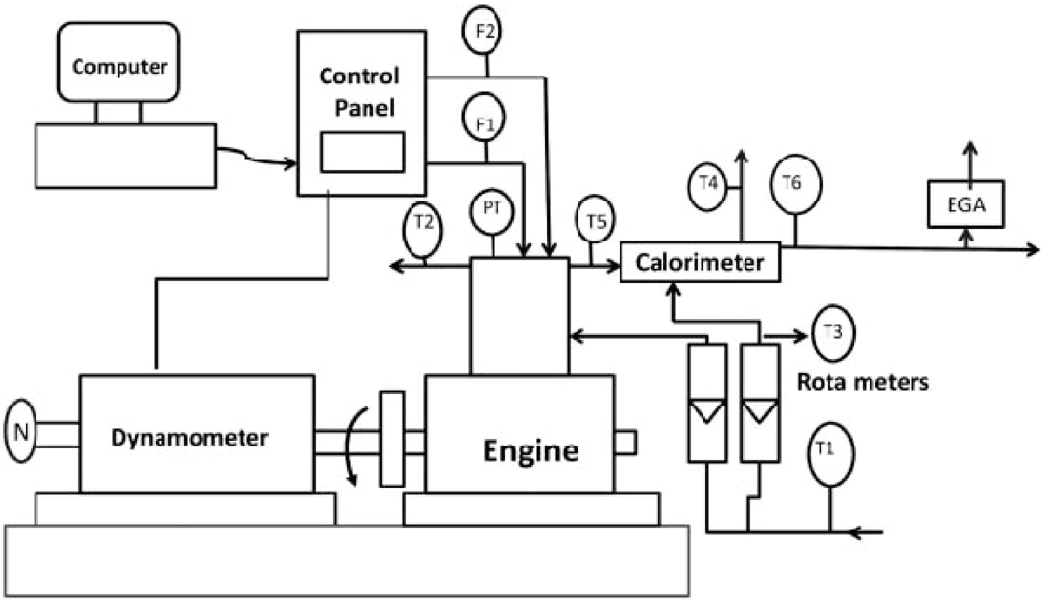

Figure 2. Line diagram of variable compression engine experimental setup.

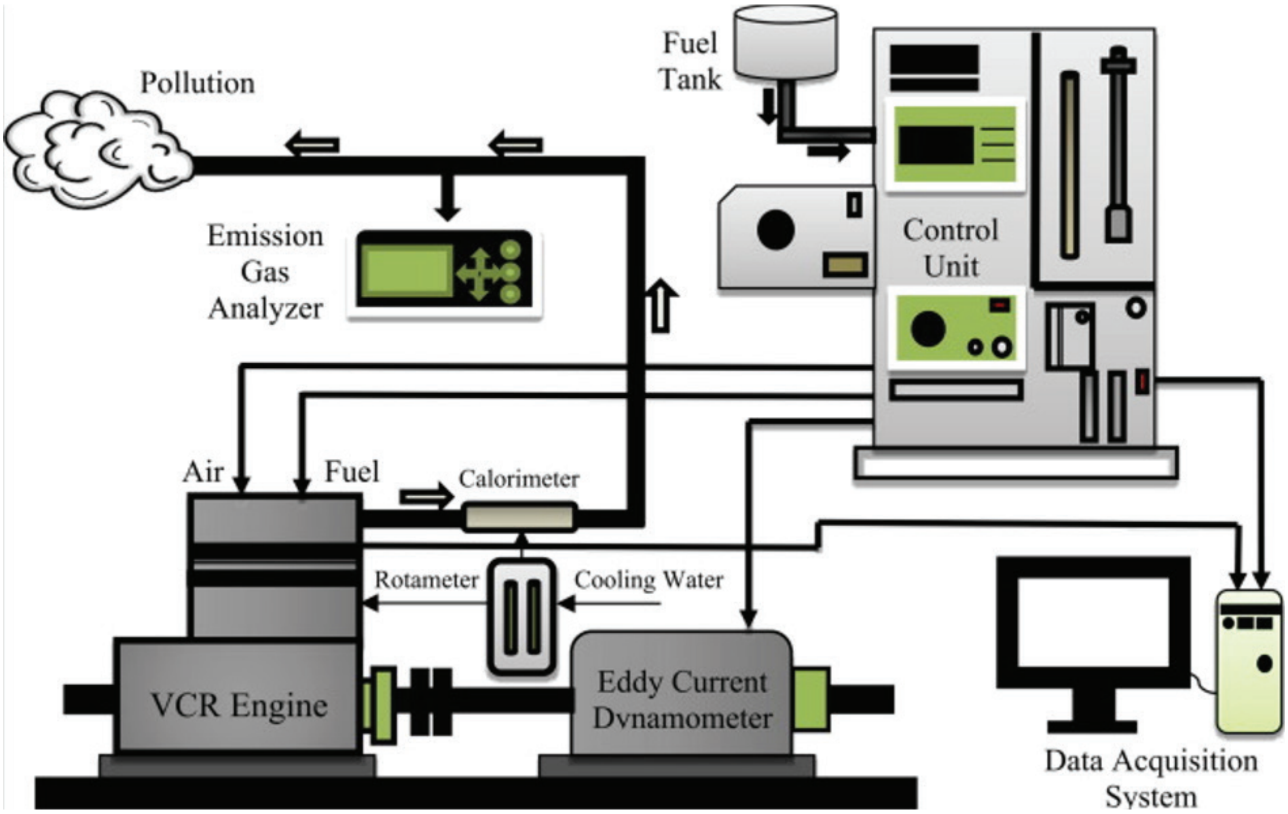

Figure 3. Schematic diagram of variable compression engine experimental setup.

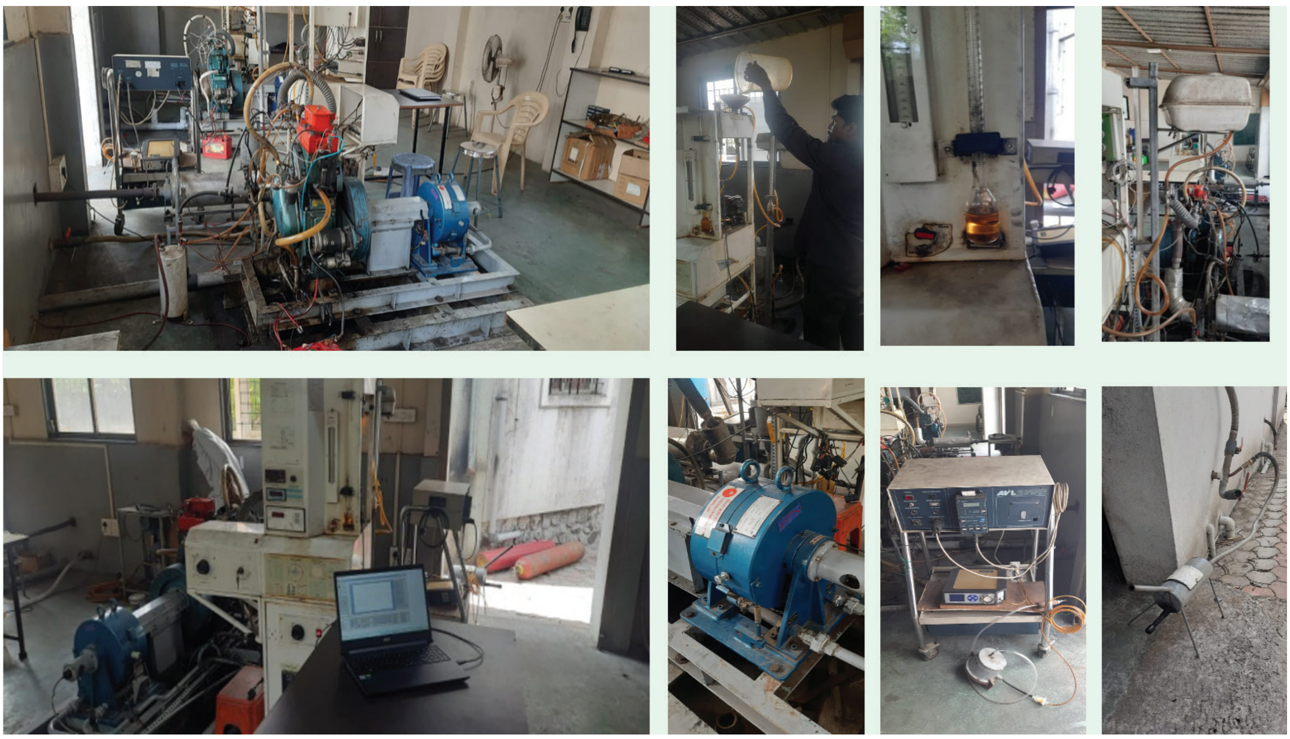

Figure 4. Variable compression engine experimental setup (Engine, Flue inlet system, flow measurement, control system, dynamometer, and Exhaust gas analyser system).

Table 2. VCR engine details

Power 3.50 kW @ 1500 rpm	Single cylinder	Four strokes	Constant speed
Water cooled	Diesel engine	Cylinder bore 87.50 (mm)	Stroke length 110.00 (mm)
Connecting rod length 234.00 (mm)	Compression type VCR	Compression ratio 14:1 to 22:1	Variable compression ratio engine - swept volume 661.45 (cc)

N -Engine speed measurement.

Figure 3 represents the schematic diagram of variable compression engine experimental setup and Figure 4 shows the variable compression engine experimental setup (Engine, Flue inlet system, flow measurement, control system, dynamometer, and Exhaust gas analyser system).

VCR Engine Parameters and Features

Detail specifications of VCR engine shown in Table 2.

The VCR engine setup offers several advanced features, including the ability to change the compression ratio without halting the engine and maintaining the combustion chamber geometry. It supports dual-fuel testing and provides real-time performance analysis with PV and performance plots. The system allows online measurements, data logging, editing, printing, and export of configurable graphs, along with detailed combustion analysis. The setup enables comprehensive evaluation of engine performance parameters such as BP, IP, FP, BMEP, IMEP, brake thermal efficiency, indicated thermal efficiency, mechanical efficiency, volumetric efficiency, specific fuel consumption, and air-fuel ratio. Additionally, it facilitates emission testing for CO, CO_2, HC, and NOx levels.

Figure 5. Exhaust gas analyzer (HG 540).

Emission Measurement

All emissions, including CO, CO_2, unburned hydrocarbons (UHC), NOx, and unused oxygen, were measured using the AIRREX HG-540 Gas Emission Analyzer, as shown in Figure 5. One end of the analyzer›s cable was connected to the analyzer's inlet, while the other was attached to the engine›s exhaust outlet. To ensure proper functionality, the analyzer requires continuous charging. Actual images depict the Exhaust Gas Analyzer fitted at the exhaust exit of the engine. The analyzer features an automatic «zero-setting» mechanism, which resets the sensor using fresh air. When the analyzer is powered on, it requests a zero setting at 10, 20, and 30-minute intervals, and continues to request it every 30 minutes thereafter. The zero port enables the gas analyzer to reset to zero even while the sampling probe is still connected to the exhaust tail. Ambient air is drawn through a charcoal filter to help reduce hydrocarbon (HC) levels to zero. To zero the CO, CO_2, and NOx readings, the analyzer uses a keyboard function that is calibrated to 20.34% oxygen by volume. The specifications of the gas analyzer used are presented in Table 3.

RESULTS AND DISCUSSION

Emission of Carbon Monoxide (CO)

At lower compression ratios, the engine may not reach the ideal combustion temperatures and pressures, leading to incomplete combustion of the fuel-air mixture. This results in higher CO emissions, as CO is produced when carbon in the fuel is not fully oxidized. Increasing the compression ratio generally enhances engine efficiency by promoting more complete fuel combustion, thereby reducing CO emissions. There is typically an optimal range of compression ratios where CO emissions are minimized, as the engine maintains a balance between

Table 3. Gas analyzer specification

Model	HG – 540- Automotive gas analyzer
Emission measuring	CO, CO_2, HC, O_2 and NOx,
Method of measuring	CO, CO_2, HC, — NDIR (Non-dispersive method infrared) O_2, NOx (electro chemical)
Repeatability	Less than + 2% FS
Response time	Within 15 seconds (more than 90%)

sufficient combustion temperature and pressure while avoiding knocking. The effect of compression ratio on CO emissions also depends on the engine load. At higher loads, the need for a richer fuel mixture can increase CO emissions, potentially negating the advantages of a higher compression ratio if not properly managed. In conclusion, varying compression ratios, combined with neem oil-based biodiesel blending, can significantly contribute to reducing CO emissions. The experimental study concluded that CO emissions decrease with an increase in both the biodiesel blending ratio and compression ratio. Figure 6 to 10 shows the effect of variation in compression ratio on CO emission at zero, 3, 6, 9 and 12 N-m loads for different blends.

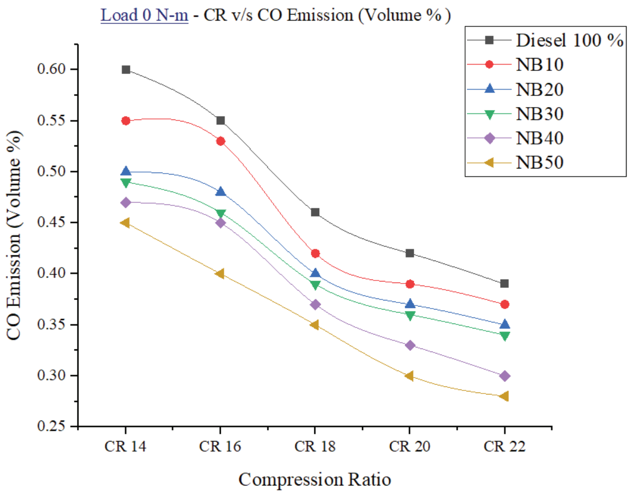

Figure 6. Effect of compression ratio on CO emission at zero load.

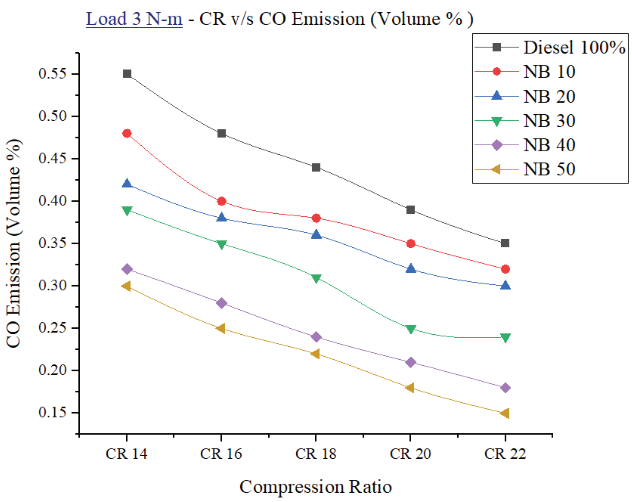

Figure 7. Effect of compression ratio on CO emission at 3 N-m load.

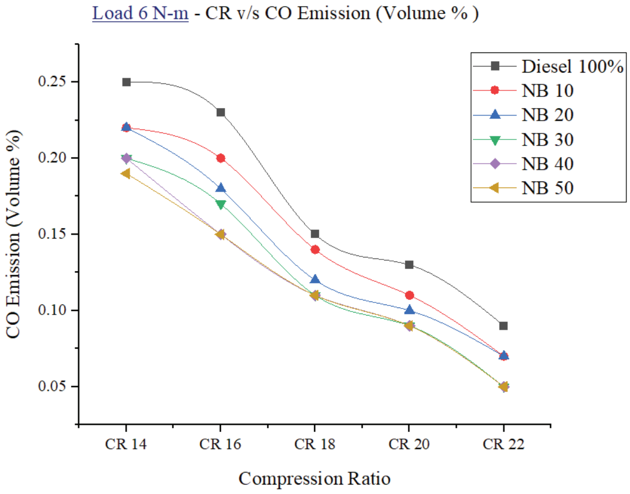

Figure 8. Effect of compression ratio on CO emission at 6 N-m load.

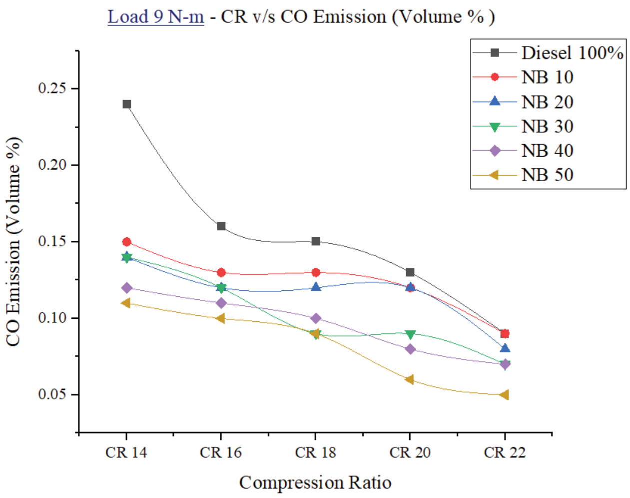

Figure 9. Effect of compression ratio on CO emission at 9 N-m load.

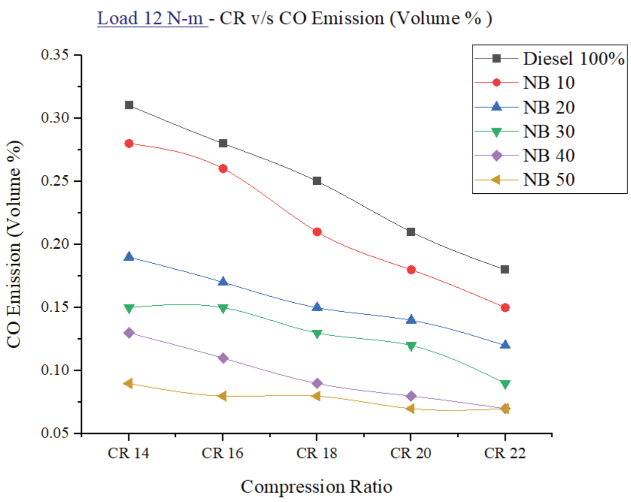

Figure 10. Effect of compression ratio on CO emission at 12 N-m load.

Emission of Carbon Monoxide (CO_2)

At lower compression ratios, the engine may not reach the ideal temperature and pressure for optimal combustion, resulting in less efficient fuel burning. To make up for this inefficiency, more fuel may be required to meet power demands. While incomplete combustion primarily affects CO emissions, increased fuel consumption typically leads to higher CO_2 emissions. On the other hand, higher compression ratios generally improve the engine's thermal efficiency, allowing it to convert more of the fuel's energy into useful work, rather than losing it as heat. As a result, less fuel is needed to generate the same amount of power, which typically results in lower CO_2 emissions per unit of power output. Under both zero load and full load conditions, CO_2 emissions decrease significantly. The study shows that using neem oil biodiesel at a compression ratio of 22 results in an approximate 20% reduction in CO_2 emissions. This significant decrease can be attributed to the cleaner combustion process facilitated by the higher oxygen content in biodiesel and the improved combustion efficiency at higher compression ratios. Figure 11 to 15 shows the effect of variation in compression ratio on CO_2 emission at zero, 3, 6, 9 and 12 N-m loads for different blends.

Emission of Hydro Carbon (HC)

Hydrocarbon (HC) emissions refer to unburned or partially burned fuel that escapes the engine through the exhaust. At lower compression ratios, combustion may be less efficient due to reduced temperatures and pressures, which can result in incomplete burning of the fuel-air

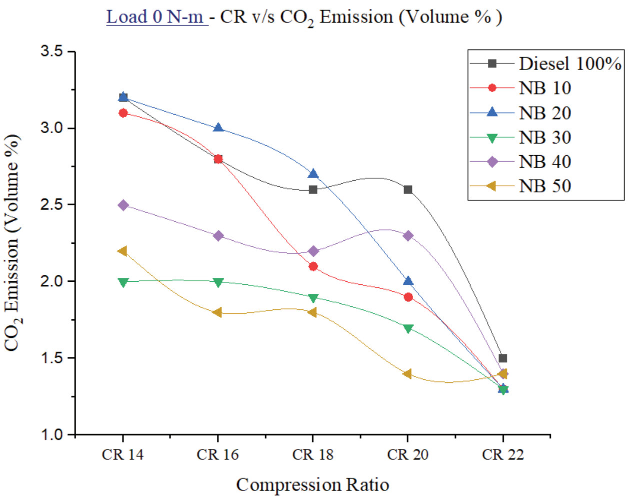

Figure 11. Effect of compression ratio on CO_2 emission at zero load.

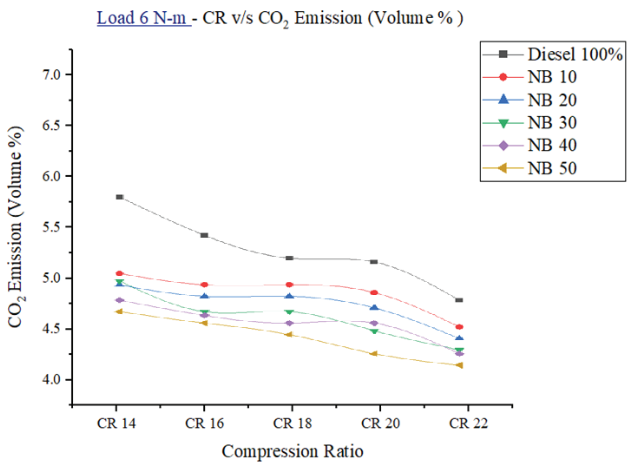

Figure 13. Effect of compression ratio on CO_2 emission at 6 N-m load.

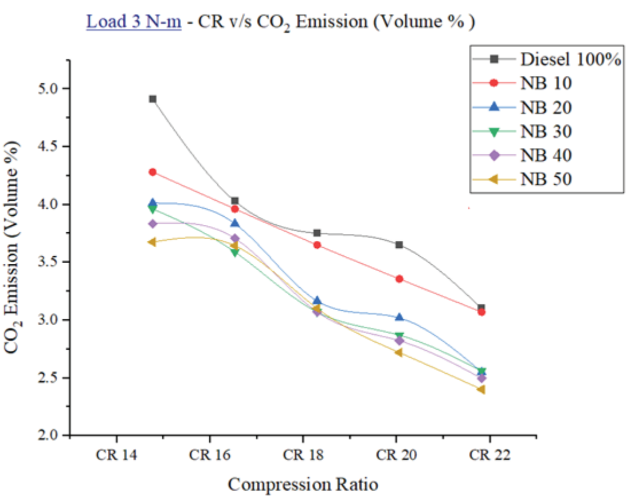

Figure 12. Effect of compression ratio on CO_2 emission 3 N-m load.

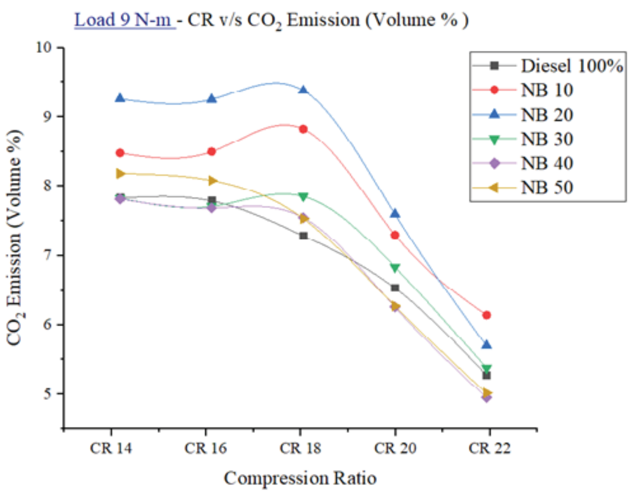

Figure 14. Effect of compression ratio on CO_2 emission at 9 N-m load.

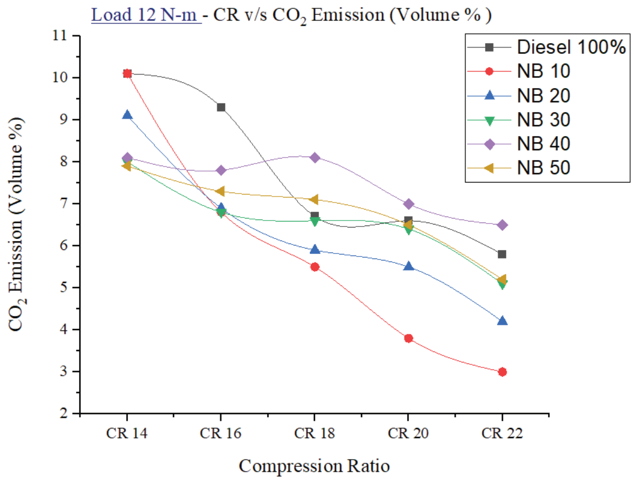

Figure 15. Effect of compression ratio on CO_2 emission at 12 N-m load.

mixture and lead to higher HC emissions. Under these conditions, more unburned or partially burned fuel is expelled as HC emissions. Increasing the compression ratio improves combustion efficiency by allowing the engine to operate at higher temperatures and pressures. This typically results in lower HC emissions, as more of the fuel is fully burned. However, if the compression ratio becomes too high, engine knocking or pre-ignition may occur, which could disrupt the combustion process and potentially increase HC emissions if not properly managed. Figure 16 to 20 shows the effect of variation in compression ratio on HC emission at zero, 3, 6, 9 and 12 N-m loads for different blends. A significant reduction in HC emissions is observed at zero, 3, 6, and 9 N-m loads with increased compression ratios and the use of neem oil biodiesel. However, there is no major change in HC emissions under full load conditions. There is approximately a 27% reduction in hydrocarbon (HC) emissions when using a B30 neem oil biodiesel blend at a compression ratio of 20 under full load conditions.

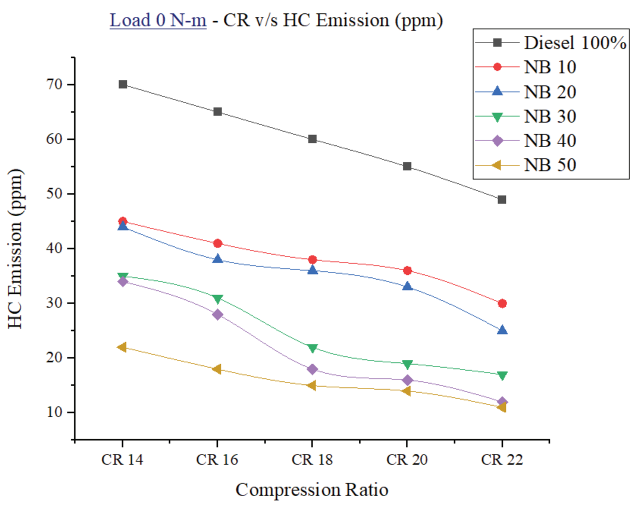

Figure 16. Effect of compression ratio on HC emission at zero load.

Emission of Oxides of Nitrogen Oxides (NOx)

Nitrogen oxides (NOx) are pollutants produced in internal combustion engines through the reaction of nitrogen and oxygen at high temperatures. NOx emissions are a significant concern due to their contribution to smog formation and potential health risks. At lower compression ratios, combustion temperatures and pressures tend to be lower, which reduces NOx formation since these gases primarily form at higher temperatures where nitrogen and

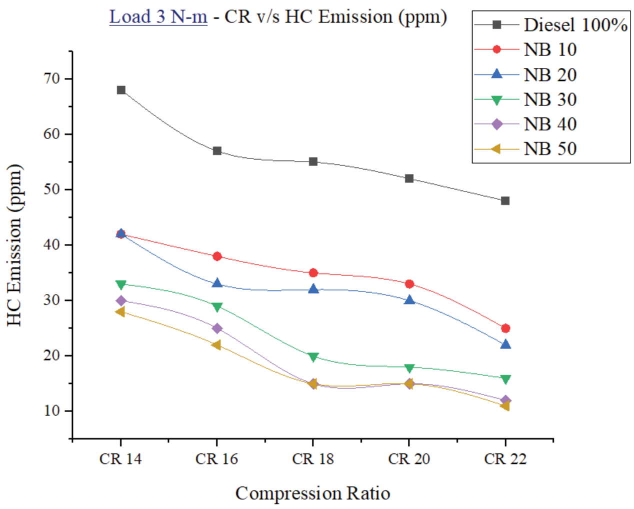

Figure 17. Effect of compression ratio on HC emission at 3 N-m load.

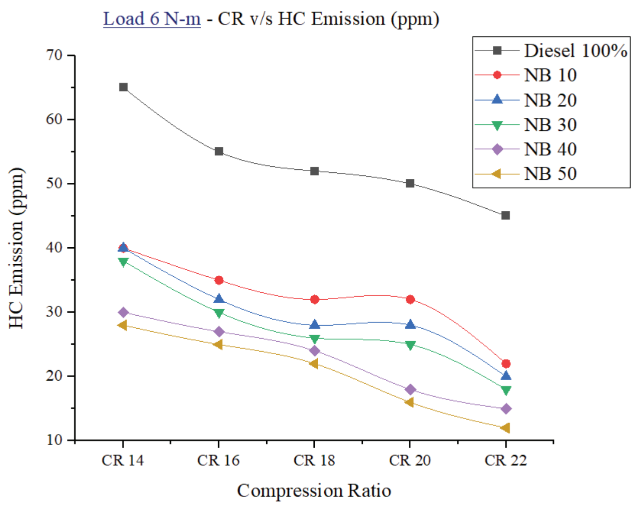

Figure 18. Effect of compression ratio on HC emission at 6 N-m load.

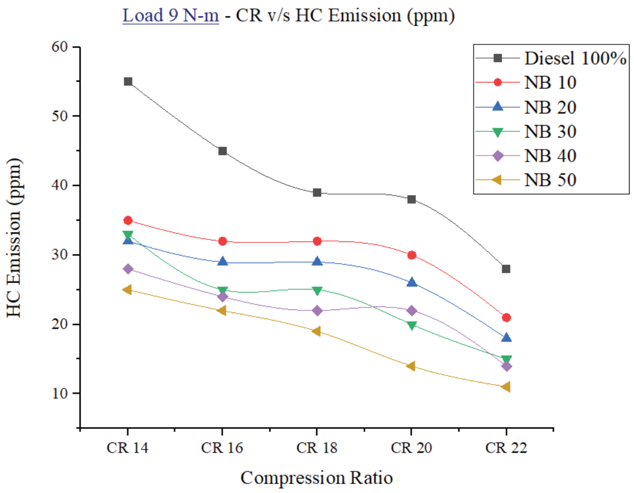

Figure 19. Effect of compression ratio on HC emission at 9 N-m load.

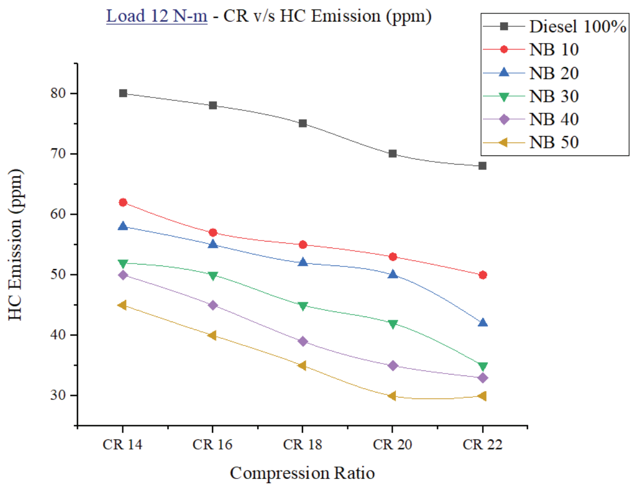

Figure 20. Effect of compression ratio on HC emission at 12 N-m load.

oxygen react more easily. When the compression ratio is increased, the engine operates at higher temperatures and pressures, accelerating the reaction between nitrogen and oxygen and thus increasing NOx formation. Figure 21 to 25 shows the effect of variation in compression ratio on NOx emission at zero, 3, 6, 9 and 12 N-m loads for different blends. As a result, NOx emissions generally raise with higher compression ratios due to the elevated combustion chamber temperatures. This presents a notable trade-off when optimizing compression ratios. To address these issues, modern engines often incorporate technologies like exhaust gas recirculation (EGR), selective catalytic reduction (SCR), and inter cooling to manage and reduce NOx emissions. It has been observed that under higher loads, engines with increased compression ratios experience higher combustion temperatures, leading to elevated NOx emissions. NOx emissions increase by 20% at full load and a higher compression ratio of 22:1 when using pure diesel.

Brake Thermal Efficiency

Brake Thermal Efficiency (BTHE) measures how efficiently an engine converts the heat from fuel combustion into useful mechanical work. It is the ratio of the engine's power output to the heat energy supplied by the fuel. Engines with lower compression ratios generally operate at lower combustion temperatures and pressures, leading to less efficient fuel-to-work conversion. Figure 26 to 30 shows the effect of variation in compression ratio on BTHE at zero, 3 6, 9 and 12 N-m loads for different blends.

As a result, more energy is lost as heat, and BTHE is lower. In contrast, higher compression ratios allow the

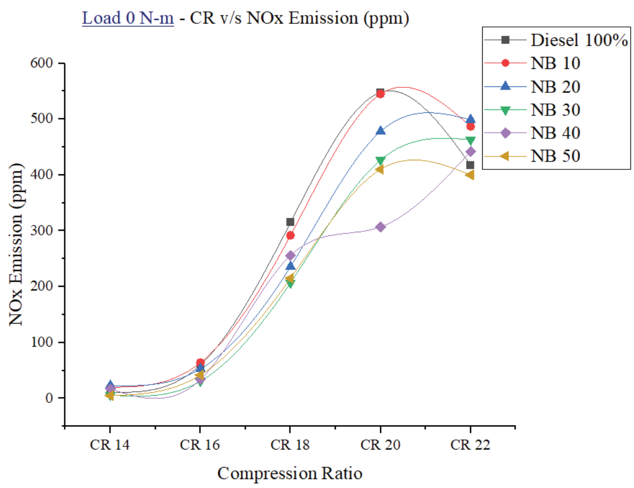

Figure 21. Effect of Compression ratio on NO_X emission at zero load.

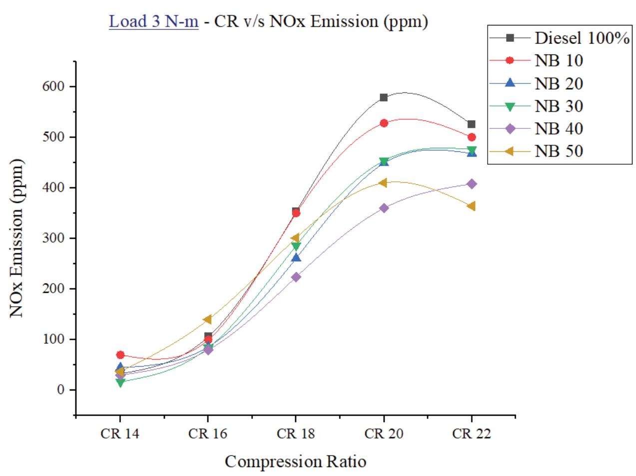

Figure 22. Effect of compression ratio on NO_X emission at 3 N-m load.

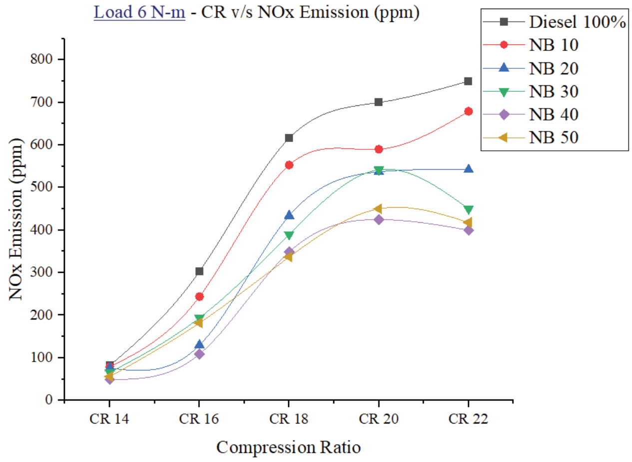

Figure 23. Effect of compression ratio on NO_X emission at 6 N-m load.

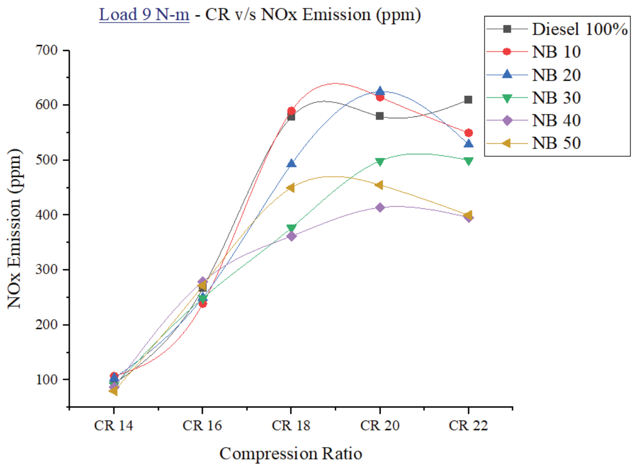

Figure 24. Effect of compression ratio on NO_X emission at 9 N-m load.

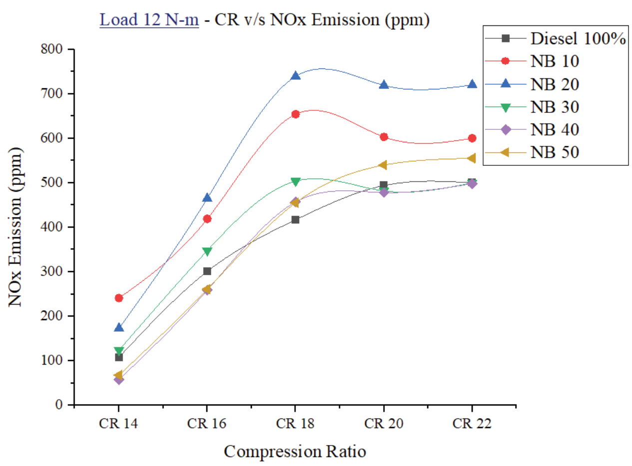

Figure 25. Effect of compression ratio on NO_X emission at 12 N-m load.

engine to operate at higher temperatures and pressures, enabling more complete fuel combustion and improving the conversion of thermal energy into mechanical work. BTHE tends to increase with biodiesel blending due to the higher oxygen content in biodiesel. This oxygen promotes more complete combustion, enhancing fuel utilization and power output, while the lower carbon content in biodiesel reduces unburned hydrocarbons, further boosting thermal efficiency. Similarly, increasing the compression ratio also improves BTHE by extracting more energy from the fuel through more efficient combustion, which reduces energy loss and converts more of the fuel's thermal energy into mechanical work.

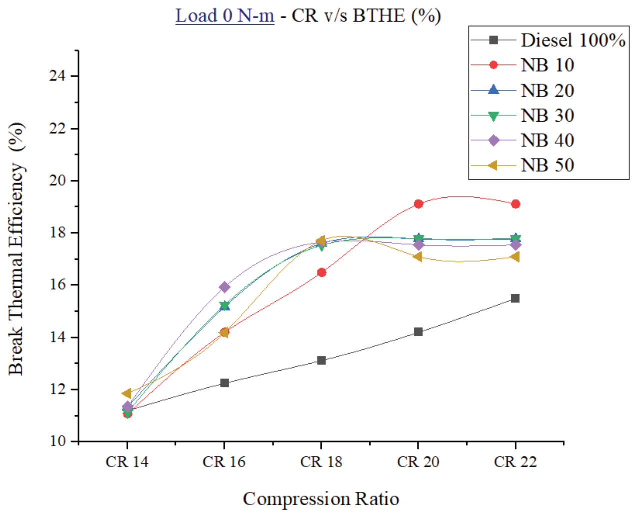

Figure 26. Effect of compression ratio on BTHE at zero load.

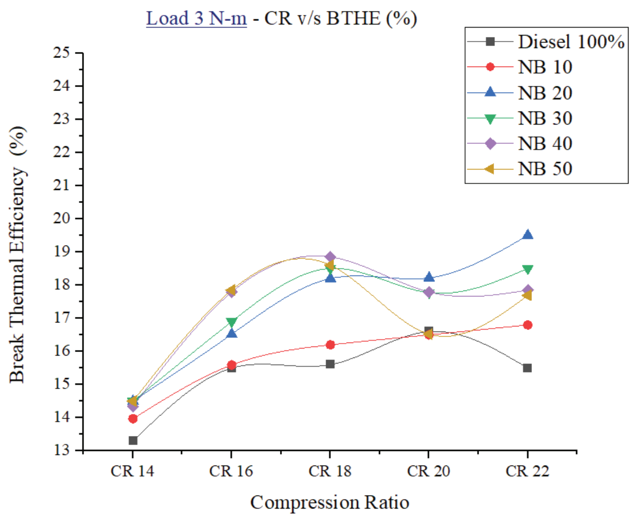

Figure 27. Effect of compression ratio on BTHE at 3 N-m load.

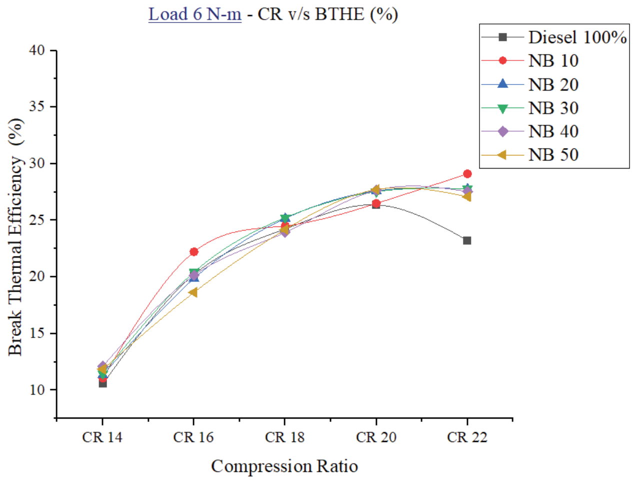

Figure 28. Effect of compression ratio on BTHE at 6 N-m load.

Specific Fuel Consumption

Specific fuel consumption (SFC) decreases with biodiesel blending due to biodiesel's higher oxygen content, leading to more complete combustion and improved fuel efficiency. Additionally, the blending reduces the need for excess fuel to achieve similar power output, contributing to lower SFC. SFC also reduces with an increase in compression ratio because higher compression enhances thermal efficiency. This is because more energy is extracted from the fuel due to better air-fuel mixture ignition, improving combustion and power generation, which ultimately reduces the fuel required per unit of power output. Thus, both factors contribute to improved engine efficiency. SFC decreases significantly under no-load conditions with a higher compression ratio and the use of NB50.Figure 31 to 35 shows the effect of variation in compression ratio on SCF at zero, 3 6, 9 and 12 N-m loads for different blends.

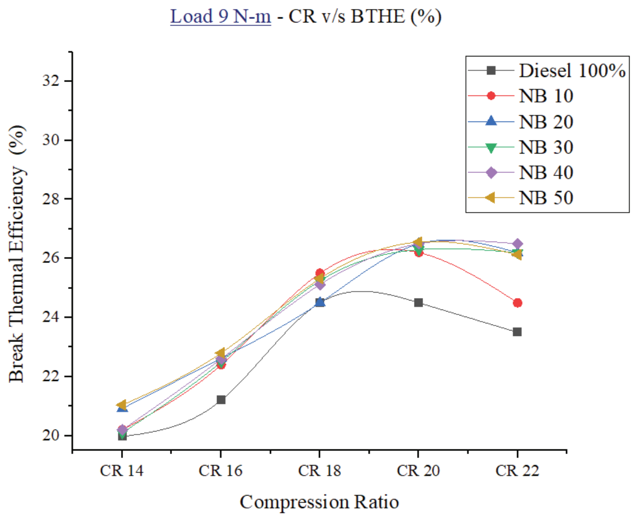

Figure 29. Effect of compression ratio on BTHE at 9 N-m load.

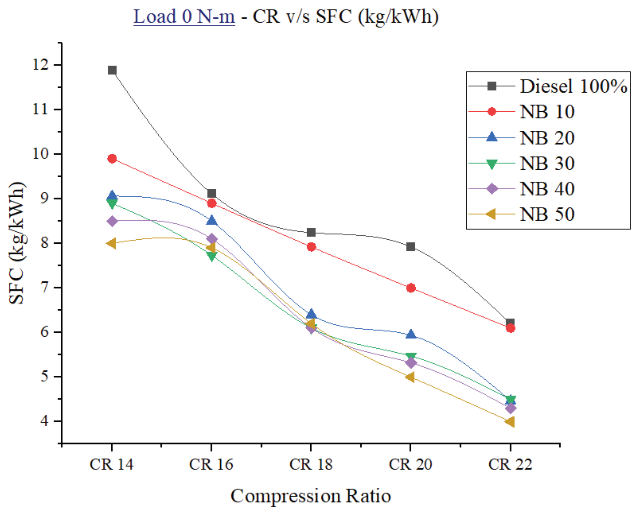

Figure 31. Effect of compression ratio on SFC at zero load.

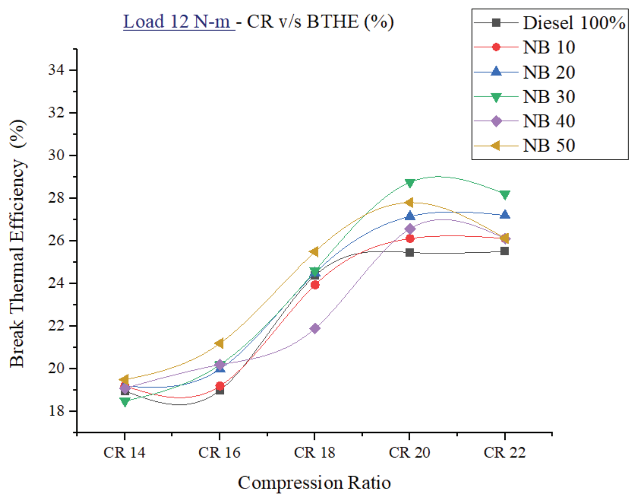

Figure 30. Effect of compression ratio on BTHE at 12 N-m load.

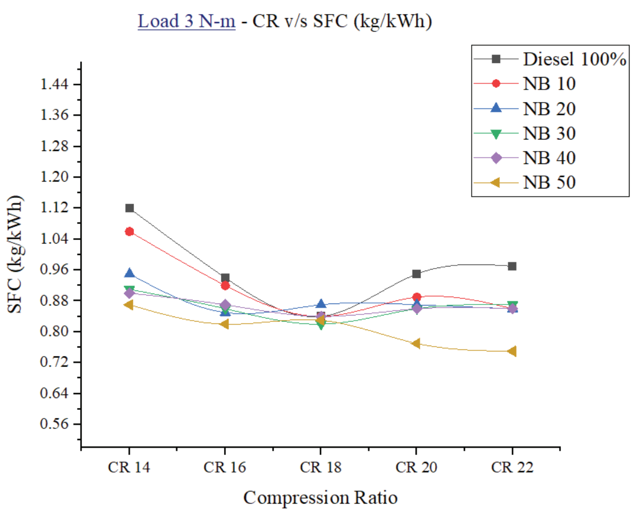

Figure 32. Effect of compression ratio on SFC at 3 N-m load.

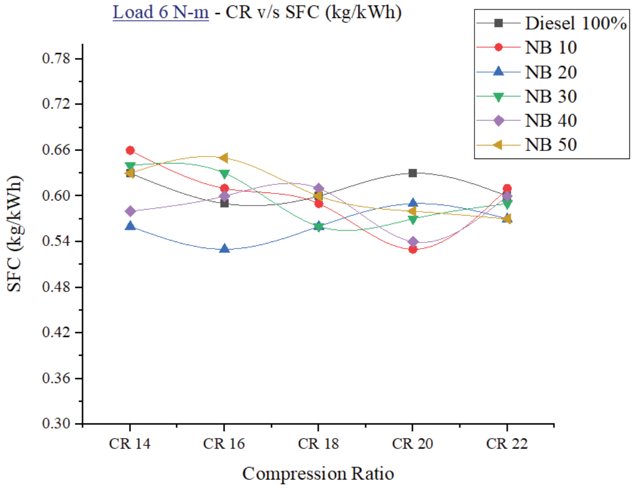

Figure 33. Effect of compression ratio on SFC at 6 N-m load.

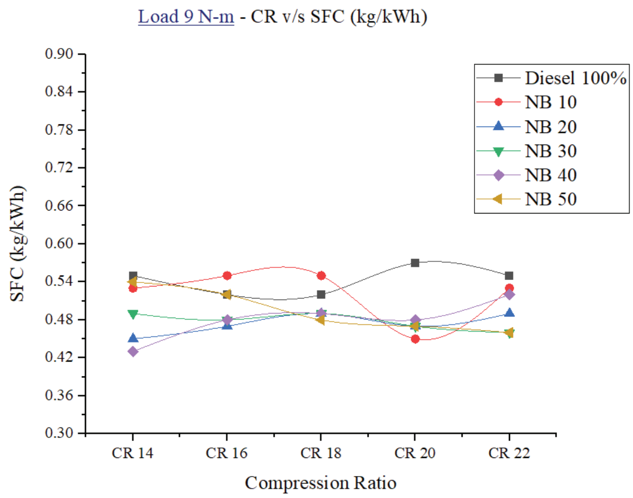

Figure 34. Effect of compression ratio on SFC at 9 N-m load.

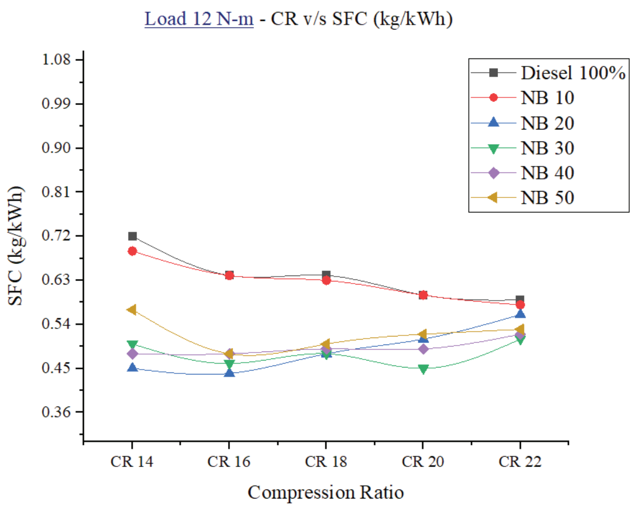

Figure 35. Effect of compression ratio on SFC at 12 N-m load.

Effect of Diesel Emissionson Environment and Health

Environmental impact and health impact

Air Pollution: Diesel engines emit several harmful pollutants, including nitrogen oxides (NOx), particulate matter (PM), hydrocarbons (HC), and carbon dioxide (CO_2). NOx contributes to the formation of ground-level ozone (smog), which reduces air quality and harms ecosystems.

Climate Change: Diesel engines release significant amounts of CO_2, a major greenhouse gas that contributes to global warming. Additionally, black carbon (a component of PM) from diesel exhaust absorbs sunlight and accelerates the melting of ice in Polar Regions, further contributing to climate change.

Acid Rain: NOx emissions from diesel engines combine with atmospheric moisture to form acids, which contribute to acid rain. Acid rain damages forests, soil, and aquatic ecosystems, leading to biodiversity loss and degradation of water quality.

Respiratory Issues: Particulate matter (PM), especially fine particles (PM2.5), can penetrate deep into the lungs, causing respiratory problems such as asthma, bronchitis, and chronic obstructive pulmonary disease (COPD). Prolonged exposure can reduce lung function and increase the risk of respiratory infections.

Cardiovascular Diseases: Long-term exposure to diesel emissions is associated with an increased risk of heart disease, high blood pressure, and stroke. PM and NOx can contribute to inflammation and oxidative stress, leading to cardiovascular complications.

Cancer: Diesel exhaust is classified as a carcinogen by the International Agency for Research on Cancer (IARC). Long-term exposure to diesel emissions, particularly PM, has been linked to an increased risk of lung cancer and possibly bladder cancer.

Neurological Effects: Emerging research suggests that long-term exposure to diesel emissions may be linked to cognitive decline and neurodegenerative diseases like Alzheimer›s, due to the presence of ultra-fine particles and toxic compounds in diesel exhaust.

TEACHING-LEARNING BASED OPTIMIZATION (TLBO) FOR MULTI-OBJECTIVE OPTIMIZATION

All testing inputs and output results are processed using MATLAB software to achieve optimal outcomes. An algorithm was developed with the assistance of Artificial Intelligence tools to obtain the most accurate results. The detailed program and optimized outcomes are outlined below.

```
clc;
clear;
close all;
```

```
% Define the number of learners (population size) and iterations
nLearners = 50;
maxIter = 100;

% Variable bounds (A, B, C)
A_min = 0; A_max = 12;
B_min = 0; B_max = 40;
C_min = 14; C_max = 22;

% Number of design variables
nVars = 3;

% Initialize population (learners)
pop = rand(nLearners, nVars);
pop(:,1) = A_min + (A_max - A_min) * pop(:,1); % A
pop(:,2) = B_min + (B_max - B_min) * pop(:,2); % B
pop(:,3) = C_min + (C_max - C_min) * pop(:,3); % C

% Objective function values for each learner
f_vals = zeros(nLearners, 6);

% Evaluate initial population
for i = 1:nLearners
    A = pop(i, 1);
    B = pop(i, 2);
    C = pop(i, 3);

    f_vals(i,1) = 1.0379 - 0.01091 * A - 0.002728 * B - 0.03762 * C; % f(X)
    f_vals(i,2) = -5.232 - 0.1025 * A - 0.03444 * B + 0.6424 * C; % f(Y)
    f_vals(i,3) = 32.25 - 1.387 * A - 0.7256 * B + 1.520 * C; % f(Z)
    f_vals(i,4) = -271.6 + 40.57 * A - 2.836 * B + 23.71 * C; % f(P)
    f_vals(i,5) = -16.21 + 0.1071 * A - 0.0190 * B + 1.0562 * C; % f(Q)
    f_vals(i,6) = 15.22 - 0.0765 * A - 0.0135 * B - 0.6956 * C; % f(R)
end
% Start TLBO process
for iter = 1:maxIter
    % Teacher Phase
    % Find the best solution (teacher)
    [~, idx] = min(sum(f_vals, 2)); % Sum of objectives (for simplicity)
    teacher = pop(idx, :);

    % Teaching factor Tf
    Tf = randi([1,2], 1);

    % Update learners
    for i = 1:nLearners
        new_pop = pop(i,:) + rand(1, nVars) .* (teacher - Tf * mean(pop));

        % Check variable bounds
        new_pop(1) = max(min(new_pop(1), A_max), A_min); % A
        new_pop(2) = max(min(new_pop(2), B_max), B_min); % B
        new_pop(3) = max(min(new_pop(3), C_max), C_min); % C
        % Evaluate new population
        A = new_pop(1);
        B = new_pop(2);
        C = new_pop(3);
        f_new(1) = 1.0379 - 0.01091 * A - 0.002728 * B - 0.03762 * C; % f(X)
        f_new(2) = -5.232 - 0.1025 * A - 0.03444 * B + 0.6424 * C; % f(Y)
        f_new(3) = 32.25 - 1.387 * A - 0.7256 * B + 1.520 * C; % f(Z)
        f_new(4) = -271.6 + 40.57 * A - 2.836 * B + 23.71 * C; % f(P)
        f_new(5) = -16.21 + 0.1071 * A - 0.0190 * B + 1.0562 * C; % f(Q)
        f_new(6) = 15.22 - 0.0765 * A - 0.0135 * B - 0.6956 * C; % f(R)

        % If the new solution is better, replace the old one
        if sum(f_new) < sum(f_vals(i,:))
            pop(i,:) = new_pop;
            f_vals(i,:) = f_new;
        end
    end

    % Learner Phase (pairwise learning)
    for i = 1:nLearners
        j = randi([1, nLearners], 1);

        if sum(f_vals(i,:)) < sum(f_vals(j,:))
            new_pop = pop(i,:) + rand(1, nVars) .* (pop(i,:) - pop(j,:));
        else
            new_pop = pop(i,:) - rand(1, nVars) .* (pop(i,:) - pop(j,:));
        end

        % Check variable bounds
        new_pop(1) = max(min(new_pop(1), A_max), A_min); % A
        new_pop(2) = max(min(new_pop(2), B_max), B_min); % B
        new_pop(3) = max(min(new_pop(3), C_max), C_min); % C

        % Evaluate new population
        A = new_pop(1);
        B = new_pop(2);
        C = new_pop(3);
        f_new(1) = 1.0379 - 0.01091 * A - 0.002728 * B - 0.03762 * C; % f(X)
        f_new(2) = -5.232 - 0.1025 * A - 0.03444 * B + 0.6424 * C; % f(Y)
        f_new(3) = 32.25 - 1.387 * A - 0.7256 * B + 1.520 * C; % f(Z)
        f_new(4) = -271.6 + 40.57 * A - 2.836 * B + 23.71 * C; % f(P)
        f_new(5) = -16.21 + 0.1071 * A - 0.0190 * B + 1.0562 * C; % f(Q)
        f_new(6) = 15.22 - 0.0765 * A - 0.0135 * B - 0.6956 * C; % f(R)
        % If the new solution is better, replace the old one
        if sum(f_new) < sum(f_vals(i,:))
            pop(i,:) = new_pop;
            f_vals(i,:) = f_new;
        end
    end
end

% Display the best solution
[~, idx] = min(sum(f_vals, 2));
best_sol = pop(idx, :);
best_f_vals = f_vals(idx, :);
fprintf(‹Best solution:\n A = %.4f, B = %.4f, C = %.4f\n›, best_sol(1), best_sol(2), best_sol(3));
fprintf(‹Objective function values: f(X) = %.4f, f(Y) = %.4f, f(Z) = %.4f, f(P) = %.4f, f(Q) = %.4f, f(R) = %.4f\n›, best_f_vals);
```

Optimum solution:

A = 0.0000, B = 40.0000, C = 22.0000

Objective function values: f(X) = 20.2021, f(Y) = 23.8400, f(Z) = 24.5060, f(P) = -23.1000, f(Q) = -21.8320, f(R) = 24.9416

Where,X represent CO emission, Y of CO_2, Z of HC, P of NOx, Q of BTHE and R of SFC. Here, minus sign represents the increase value in percentage.

UNCERTAINTY ANALYSIS

Due to the degree of uncertainty of the measuring equipment used, an uncertainty analysis is performed for the measurements of the engine performance parameters. For the development of the uncertainty analysis, the Type A evaluation method was used, which is based on the statistical analysis of a set of measurements (x_1, x_2, x_3…….x_n). The best estimate of a measurement set ($\bar{x}$) is determined by equation (1).

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (1)$$

The calculation of the dispersion of the measurements ($\bar{s}$) is carried out using the standard deviation, as shown in equation (2).

$$\bar{s} = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}} \quad (2)$$

The measurement uncertainty (μ) used is determined from the calculation of the mean, standard deviation, as shown in equation (3).

$$\mu = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n\cdot(n-1)}} \quad (3)$$

The experimental tests were replicated three times (n=3) for each mode of operation and each type of fuel since a higher number implies a longer experimentation time, which could aggravate the uncertainty of the measurements. The uncertainty of each measured parameter for CO is shown in Table 4. Whereas the uncertainty analysis for CO_2, HC, NOx, BTHE and SFC are presented in the Table 5 to 9. Summary of uncertainty in parameters of engine emission and performance is presented in Table 10.

In the experimental engine setup certain quantiles required to measure like temperature at various points, load variation, fuel flow, air flow, water flow, speed etc. using sensors. The all sensors are checked and calibrated for all measuring quantities of temperature (±0.5%), load (±0.25% of F.S), fuel flow (±0.1% of span), air flow (±0.5%),

Table 4. Uncertainty analysis of CO

Step 1	Step 2	Step 3
$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$	$\bar{s} = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}}$	$\mu = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n\cdot(n-1)}}$
$\bar{x} = \frac{34.36}{150}$	$\bar{s} = \sqrt{\frac{5587.5}{149}}$	$\mu = \sqrt{\frac{5587.5}{22350}}$
$\bar{x} = 0.22$	$\bar{s} = \sqrt{37.5}$	$\mu = \sqrt{0.2567}$
	$\bar{s} = 6.12$	$\boldsymbol{\mu = 0.50}$

Table 5. Uncertainty analysis of CO_2

Step 1	Step 2	Step 3
$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$	$\bar{s} = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}}$	$\mu = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n\cdot(n-1)}}$
$\bar{x} = \frac{741.9}{150}$	$\bar{s} = \sqrt{\frac{710.26}{149}}$	$\mu = \sqrt{\frac{710.26}{22350}}$
$x = 4.96$	$\bar{s} = \sqrt{4.766}$	$\mu = \sqrt{0.03177}$
	$\bar{s} = 2.18$	$\boldsymbol{\mu = 0.17}$

Table 6. Uncertainty analysis of HC

Step 1	Step 2	Step 3
$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$	$\bar{s} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$	$\mu = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n \cdot (n-1)}}$
$\bar{x} = \frac{5142}{150}$	$\bar{s} = \sqrt{\frac{73239.38}{149}}$	$\mu = \sqrt{\frac{73239.38}{22350}}$
$\bar{x} = 34.28$	$\bar{s} = \sqrt{491.53}$	$\mu = \sqrt{3.27}$
	$\bar{s} = 22.17$	$\boldsymbol{\mu = 1.81}$

Table 7. Uncertainty analysis of NO_x

Step 1	Step 2	Step 3
$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$	$\bar{s} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$	$\mu = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n \cdot (n-1)}}$
$\bar{x} = \frac{50046}{150}$	$\bar{s} = \sqrt{\frac{62156}{149}}$	$\mu = \sqrt{\frac{62156}{22350}}$
$\bar{x} = 333.64$	$\bar{s} = \sqrt{417.15}$	$\mu = \sqrt{2.78}$
	$\bar{s} = 20.42$	$\boldsymbol{\mu = 1.66}$

Table 8. Uncertainty analysis of BTHE

Step 1	Step 2	Step 3
$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$	$\bar{s} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$	$\mu = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n \cdot (n-1)}}$
$\bar{x} = \frac{3043.75}{150}$	$\bar{s} = \sqrt{\frac{3723}{149}}$	$\mu = \sqrt{\frac{3723.8}{22350}}$
$\bar{x} = 20.29$	$\bar{s} = \sqrt{24.99}$	$\mu = \sqrt{0.166}$
	$\bar{s} = 4.99$	$\boldsymbol{\mu = 0.40}$

Table 9. Uncertainty analysis of SFC

Step 1	Step 2	Step 3
$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$	$\bar{s} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$	$\mu = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n \cdot (n-1)}}$
$\bar{x} = \frac{289.13}{150}$	$\bar{s} = \sqrt{\frac{1117.23}{149}}$	$\mu = \sqrt{\frac{1117.}{22350}}$
$\bar{x} = 1.92$	$\bar{s} = \sqrt{7.49}$	$\mu = \sqrt{0.0499}$
	$\bar{s} = 2.73$	$\boldsymbol{\mu = 0.22}$

Table 10. Uncertainty in parameters of engine emission and performance

Measurement	Uncertainty
CO	±0.5
CO_2	±0.17
HC	±1.81
NOx	±1.66
SFC	±0.22
Break thermal efficiency	±0.40

water flow(±2% of full), speed (±0.25%). The parameters measured are within specified accuracy range of the respective sensors. The calibration certification of all measuring devices is provided by the Apex Innovations Pvt. Ltd., Sangli, Maharashtra.

CONCLUSION

The following conclusions are drawn from the current experimental study:

- Experimental observations indicate that CO emissions decrease with an increase in biodiesel blending, as well as with a higher compression ratio. The most significant reduction in CO emissions is was observed with a 50% neem biodiesel blend (NB50) at a moderate load of 6 N-m and a compression ratio of 22, achieving a 28% decrease.
- CO_2 emissions are reduced by 20% when using a B40 biodiesel blend at a compression ratio of 22 under full load conditions of 12 N-m. This reduction can be attributed to the enhanced combustion efficiency and the cleaner-burning properties of the biodiesel blend, leading to lower carbon dioxide output during operation.
- Approximately a 27% reduction found in hydrocarbon (HC) emissions when using a B30 neem oil biodiesel blend at a compression ratio of 20 under full load conditions.
- NO_X emissions increase by 20% at full load and a higher compression ratio of 22:1 when using pure diesel. To address these issues, modern engines often incorporate technologies like exhaust gas recirculation (EGR), selective catalytic reduction (SCR), and inter cooling to manage and it can reduce NOx emissions.
- Brake Thermal Efficiency increases with both load and compression ratio. A 16% increase in BTHE was observed when using NB30 at a 6 N-m load with a compression ratio of 22:1.
- SFC decreases significantly under no-load conditions with a higher compression ratio (22:1) and the use of NB50.
- Optimal results from AI-TLBO at no-load conditions using NB40 fuel and a compression ratio of 22 show a 20.20% reduction in CO emissions, a 23.84% decrease in CO2, and a 24.5% reduction in HC. However, NOx emissions increased by 23.1%, while BTE improved by 21.82%, and SPC decreased by 24.94% compared with 100 % diesel fuel.

NOMENCLATURE

BP	Brake Power
BMEP	Brake Mean Effective Pressure
BSFC	Break Specific Fuel Consumption
BTE	Brake Thermal Efficiency
IMEP	Indicated Mean Effective Pressure
IP	Indicated Power
MEP	Mean Effective Pressure
Nm	Newton-meter (Torque)
RPM	Revolutions Per Minute
NOx	Nitrogen Oxides
PM	Particulate Matter
CO	Carbon Monoxide
NaOH	sodium Hydroxide
HC	Hydrocarbons
CO_2	Carbon Dioxide
O_2	Oxygen
VCR	Variable Compression Engine
BSFC	Brake Specific Fuel Consumption
JTME	Jetropha Methyl Ester
UBH	Unborn Hydro Carbon
EGR	Exhaust Gas Recirculation
LPG	Liquidity Petroleum Gas
CNG	Compressed Natural Gas
H_2SO_4	Sulfuric Acid
CR, R	Compression Ratio
η	Efficiency
SFC	Specific Fuel Consumption
ppm	Parts Per Million
MENO	Methyl Easter Neem Oil
ASTM	American Society for Testing and Materials
NB10	Neem oil base biodiesel (10 % Neem oil and 90 % Diesel)
NB20	Neem oil base biodiesel (20 % Neem oil and 90 % Diesel)
NB30	Neem oil base biodiesel (30 % Neem oil and 90 % Diesel)
NB40	Neem oil base biodiesel (40 % Neem oil and 90 % Diesel)
NB50	Neem oil base biodiesel (50 % Neem oil and 90 % Diesel)
TLBO	TEACHING-LEARNING BASED OPTIMIZATION

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DISCLOSURE OF INTEREST

The authors report there are no competing interests to declare.

FUNDING DETAILS

The current research work was not supported by any funding agency.

ETHICS

There are no ethical issues with the publication of this manuscript.

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