EXPERIMENTAL STUDIES ON CI ENGINE PERFORMANCE AND EMISSIONS USING NEEM-BASED BIODIESEL AS AN ALTERNATIVE FUEL

Muthuraman Subbiah[1], Sivaraj Murugan[2], Kumar Ayyappan[3]

[1] Department of Engineering, University of Technology and Applied Sciences, Muscat, Oman
[2] Department of Mechanical Engineering, Rohini College of Engineering and Technology, TN- India
[3] Department of Applied Sciences, Amrita College of Engineering and Technology, TN- India
e-mail: muthu9678@gmail.com

The depletion of fossil fuels and increasing greenhouse gas emissions have intensified interest in biodiesel as a feasible substitute for fossil fuels. Biodiesel has multiple benefits, such as its renewability and reduced emissions of toxic exhaust upon combustion. This study examines the generation of Neem seed biodiesel and its impact on the performance of compression ignition (CI) engines when combined with pure diesel. The biodiesel was produced by the transesterification process. Transesterification occurred in two phases: acid catalysis and base catalysis. Three unique blends were produced by amalgamating neem biodiesel with pure diesel (B10, B15, and B20). The performance of various combinations was evaluated and contrasted with that of pure diesel. As the load increased, the brake thermal efficiency and specific fuel consumption of all blends enhanced. Hydrocarbons, carbon monoxide, and smoke opacity were diminished in comparison to pure diesel. Nitrogen oxides increased with load in all mixes relative to pure diesel. This study indicates that neem-based biodiesel serves as a viable alternative to conventional diesel.

Keywords: biodiesel, Alternate Fuels, diesel engine performance, emissions, Neem biodiesel

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1. Introduction

The advancement of society has consistently depended on energy. The extraction of fossil fuels has consistently been an unsustainable and ecologically detrimental activity. The global energy issue negatively impacts numerous impoverished and developing countries. The utilisation of technology has progressively diminished the level of difficulty. Researchers are creating sustainable energy alternatives to diminish reliance on fossil fuels, addressing two concerns: the reduction of pollution from fossil fuel combustion and the conservation of fossil fuels for future generations. Biofuel constitutes one element of this expansion [1-2]. Alternative fuel sources have been pursued in response to stringent laws, heightened pollution, and escalating fuel costs. The production of biodiesel has gained considerable attention in recent years owing to increasing environmental and energy concerns. Due to biodiesel blending regulations in several countries, the demand for biodiesel has increased significantly. Biodiesel has numerous advantages over fossil fuels, such as its renewability, biodegradability, and reduced emissions. The organic carbon in biodiesel originates from photosynthesis in plants; therefore, it does not contribute to hazardous pollutants such as carbon dioxide and sulphur dioxide. Due to its higher flashpoint, it is more secure to transport and store. Due to its lubricating properties, it extends the lifespan of engines. Consequently, biodiesel is gaining popularity as a transportation fuel in numerous countries, particularly where environmental concerns and energy security are paramount. Historically, vegetable and animal oils have been utilised in biodiesel production. Jatropha is the predominant feedstock; nonetheless, its production cost is thrice that of pure diesel [3-4].

Alternative alternatives comprised Pongamia, Mahua, animal fats, Cottonseed oil, Kopak Methyl Ester, soybean crude oil, and Rapeseed oil. Tallow methyl esters, together with palm oil, waste cooking oil, and Kopak methyl ester, were also evaluated. Lubricant thickened with vegetable oils may obstruct filters and adhere to piston rings. They may also collect in injectors and engines. Biodiesel can be produced through the transesterification of plant oils. The utilisation of biodiesel resulted in a reduction of CO_2 emissions. The implementation of a low-heat rejection engine enhanced the efficiency of biodiesel. [5-6] examined various non-edible oils, such as Madhuca Indica (Mahua), Jatropha curcas (Ratan Jyoti), and Melia Azadirachta (Neem), and determined that they are more economically advantageous than edible oils for biodiesel production. Tree-derived oilseeds, oil extraction techniques, and biodiesel manufacturing technologies were evaluated. examined wild mustard oil as a source of biodiesel. The transesterification of neem oil with methanol, catalyzed by sodium methoxide, yielded biodiesel at a concentration of 94 % by weight. Prior studies, such as Gupta et al. [8], investigated fuel blends comprising 5 %, 10 %, and 20 % citrus Sinensis biodiesel combined with conventional diesel. Blended biodiesel demonstrated equivalent performance and exhaust emissions compared to pure biodiesel throughout testing. The utilisation of Citrus Sinensis biodiesel in the engine produced just a negligible effect on power and torque. Emission tests indicate that citrus Sinensis biodiesel elevates NO_x levels. Simultaneously, it reduces carbon monoxide (CO). [9] examined engine performance and emissions by evaluating Mahua biodiesel and its assorted fuel blends in a single-cylinder diesel engine. Researchers employed a mixture of selective catalytic reduction, cold exhaust gas recirculation, and hot exhaust gas recirculation to mitigate NO_x emissions. In comparison to a conventional engine operating at maximum capacity without any mitigation strategies, the outcomes were notably remarkable. In a standard diesel engine utilising a B100 biodiesel blend, the SCR significantly decreases nitrogen oxide emissions relative to alternative technologies. A 20 % reduction in NO_x emissions was anticipated for B100 blended fuel engines utilising SCR technology. [10] investigated the performance of biodiesel derived from soya and mustard oils. The thermal efficiency of the mixtures was determined to be analogous to that of petrol. [11] observed that the fatty esters in biodiesel directly influence its characteristics. The interplay of fat and alcohol components can influence cetane number, cold flow rate, stability, viscosity, and lubricity. Augmented chain length and unsaturation enhance the cetane number, melting temperature, and viscosity of unrefined fatty substances. Isopropyl esters seem to surpass methyl esters regarding fuel properties. Isopropanol is more expensive than methanol, and transesterification is essential for its economic viability. [12] investigated low-cost, high-Fatty Acid content feedstock for the production of fuel-quality biodiesel. Feedstock with elevated free fatty acid (FFA) levels cannot be treated using traditional alkali-catalyzed transesterification techniques. This transpires when alkaline catalysts interact with fatty acid esters (FAEs). Soap functions as a catalyst in this process, inhibiting the separation of glycerin and ester. Triglycerides were transformed utilising an acid catalyst that diminished the free fatty acid concentration of high free fatty acid feedstock to below 1 %. In the experiment, soybean oil containing less than 20 % palmitic acid was utilised to replicate a high FFA feedstock. The study indicates that acid-catalyzed pretreatment may reduce the feedstock's free fatty acid concentration to below 1 %. Acid catalysts and methanol were required for yellow and brown grease. [13] investigated non-edible oils as a source for biodiesel. The alkali-catalyzed method was employed to synthesise biodiesel.

Transesterification of non-edible oils with elevated free fatty acid content is unfeasible. Biodiesel was produced with a two-step catalytic process. Non-food oils with free fatty acids were readily accessible for biodiesel production. [14] successfully produced biodiesel from waste cooking oils by a continuous transesterification method. Glycerol has been proposed to decrease biodiesel production costs. The procedures employed to produce biodiesel included transesterification and pyrolysis (thermal cracking). The predominant transesterification technique involves the transesterification of vegetables and animal lipids. Glycerides to alcohol, catalysts, reaction duration, free fatty acids, and moisture concentration in oils and fats.

Neem is a superior non-edible biodiesel feedstock due to its extensive applications. It has an average lifespan of approximately 90 years and is easily accessible. It can proliferate in nearly all environments. Following five years of development, it commences reliable fruit production. [15] tried to synthesise biodiesel from neem oil. Moisture and free fatty acid concentrations influence the yield and quality of biodiesel (FFA). The processes of esterification and transesterification were employed to generate biodiesel. The efficacy of the blends was assessed utilising a direct injection diesel engine. Biodiesel and its blends surpass mineral diesel in fuel economy and thermal efficiency. Biodiesel elevated NO_x emissions but reduced HC and CO emissions in comparison to mineral diesel. Researchers found that biodiesels derived from Neem oil had lower levels of free fatty acids compared to mineral-based fuels. The incorporation of a-tocopherol acetate into neem oil-based DI diesel decreased NO_x emissions while enhancing engine oxidation stability. Emissions were quantified via a computerised four-stroke water-cooled DI engine. Atocopherol acetate has demonstrated the capacity to enhance stability and diminish NO_x emissions in multiple industrial processes. The incorporation of A-tocopherol resulted in the increased use of particular braking energy [16-17] devised a two-step reaction method for the production of biodiesel from neem seeds. The kinematic viscosity, density, and flashpoint of the biodiesel were measured using standard ASTM methods, while short-chain alcohols (e.g., methanol) were utilized in the transesterification process. [18] investigated the attributes of neem oil-derived biodiesel synthesis and the fuel parameters of neem biodiesel mixtures. Research indicated that consistent planting and harvesting of neem oil could potentially reduce the necessity for diesel fuel imports through biodiesel manufacturing. [19] examined the production of biodiesel from neem oil. The biodiesel produced through transesterification had the highest yields, and the most significant experimental conditions were identified. Biodiesel was synthesised at several temperatures and molar ratios of oil to alcohol. The utilisation of biodiesel as a diesel fuel led to diminished smoke and carbon monoxide emissions. In contrast, NO_x emissions were constant. low volatility and polyunsaturated characteristics have influenced the substitution of triglycerides for diesel. The predominant method for producing biodiesel is transesterification, yielding monoalkyl esters from vegetable oils and fats. Transesterification is influenced by temperature, pressure, duration, and the molecular weight of the alcohol-to-glyceride conversion. Biodiesel produced from neem seed and Camelina sativa was assessed for emissions and performance in diesel engines. Methyl esters produced from Neem and Camelina Sativa oils were tested in the engine. A 1.9-liter Multijet diesel engine was utilised to evaluate engine performance. At all evaluated engine speeds, brake power (BP) and brake specific fuel consumption (BSFC) exhibited significant differences between CB10 biodiesel and diesel. CB10 biodiesel exhibits reduced average emissions compared to alternative biodiesel fuels, so contributing to pollution mitigation and environmental protection. In unmodified engines, diesel fuel may be substituted with CB10. [20] trans esterified nectar oil and incorporated 1 percent H_2SO_4 for biodiesel synthesis. The performance of B10, B20, and B30 blends was evaluated using a single-cylinder, four-stroke diesel engine. B10 surpasses other fuel blends, including diesel, in both emission and performance metrics. Due to the superior brake thermal efficiency of the B15 blend, the diesel engine exhibited lower emissions of CO, HC, and NO_x compared to pure diesel under full load of CO, HC, and NO_x compared to a diesel engine. [21] investigated the optimisation of a NO–WGO blend utilising both lower- and higher-order alcohols concerning engine performance, emissions, and combustion properties. The impact of administering and amalgamating alcohol with NO and WGO mixes was investigated under varying doses. Alcohol injection produced elevated NO_x emissions in comparison to fuel blends. [22] examined the physical and chemical characteristics of the generated biofuels. Rice wine alcohol is incorporated at 5 % into the neem methyl ester-diesel blend to enhance the performance of a single-cylinder compression ignition engine. Multiple combinations were created and evaluated in an experiment by varying engine loads while sustaining a steady speed. All emissions decreased, with the exception of nitrous oxide.

A literature study revealed a paucity of studies regarding the efficacy of neem-based biodiesel at lower blends as a diesel engine fuel. Experiments were performed on a single-cylinder diesel engine to assess the performance and emissions of neem-based biodiesel (NBBD). The results are juxtaposed with those of a pure diesel engine.

2. Methodology and materials

2.1. Neem Biodiesel Preparation

Following the heating of neem oil for five minutes at 100 °C in three-neck flasks, all water content was eliminated. A 0.1 N KOH solution in distilled water was prepared and placed in the burette to assess acidity. Three to four drops of phenolphthalein indicator were added to dilute neem oil to a volume of 10 ml. The solvent preparation for analysis commenced with the addition of Methyl Alcohol to the sample oil. The solution's acidity was assessed using titration. The acidity was established at 5 mg.g^{-1} of potassium hydroxide (KOH). Consequently, the esterification and transesterification processes were finalised. H_2SO_4 was employed as an acid catalyst for the esterification of Neem oil. Methanol and neem oil were heated to 55.5 degrees Celsius, and 1 percent H_2SO_4 acid catalyst was introduced to the mixture. A magnetic stirrer was employed to mix the solution at 60 °C for 60 minutes, during which the reaction was permitted to continue. The acid esterification procedure reduced both viscosity and acidity. Subsequent to the acid esterification process, the oil combination is extricated from the methanol, acid, and further impurities. A funnel was employed to segregate the esterified oil mixture. The solution was permitted to cool for approximately 15 minutes prior to disposal. The lower layers contained acids and significant impurities, whereas the upper layer consisted only of pure methanol. The middle oil layer is selected for the second reaction following the removal of the first two layers. Fuels like glycerol or biodiesel can be synthesised by transesterification, a process that entails the reaction of oil triglycerides with methanol in the presence of an acid catalyst. The natural form of glycerol is applicable in soap production. Biodiesel is the methyl ester of fatty acids.150 mL of methanol was subjected to a 1 % concentration of KOH as a base catalyst. The neem oil was esterified by heating the combination to 55 degrees Celsius and incorporating it into the oil. The reaction was stirred at 300 RPM at 60 °C for 60 minutes. The Transesterification solution was permitted to settle spontaneously by gravity in a conical flask. The separation of biodiesel and glycerol was conducted over a duration of 12 hours. 100 mL of oil and 100 mL of distilled water are need for aqueous purification. Water washing removes methanol and other contaminants from the ethanol production process. Nonetheless, one may elect to incorporate water with the oil. The biodiesel was subsequently dehydrated once more to ensure the highest possible quality level. From 1000 ml of crude neem oil, 750 ml of neem oil biodiesel was produced. Figure 1 illustrates the several phases of neem biodiesel production.

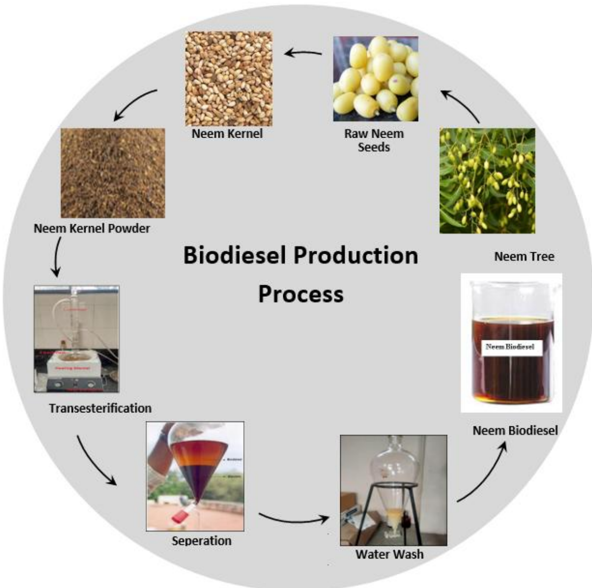

Fig. 1 Steps involved in neem biodiesel production process

2.2. Experimental conditions of CI engine tests

Engine speed: Constant at 1800 RPM (from Table 1).

Test duration: For each blend (B0, B10, B15, B20), tests were conducted at incremental loads (25 %, 50 %, 75 %, 100 %) with stabilization periods.

Tab. 1 Test Engine Specifications

Make	Kirloskar*
Engine	Water-cooled, single-cylinder, four-stroke diesel engine with a power of 5 kW @ 1800 RPM
Stroke × Bore (mm)	110 × 85
Cylinder capacity (cm^3)	660
Compression Ratio	16
Dynamometer	Type eddy current, water-cooled
Piezo sensor	Range 5000 PSI with low noise cable
Data acquisition system	NI USB-6210, 16 bit, 250 kS/s
Temperature Sensors	Type RTD, PT100, and K-type thermocouple
Load indicator	Load cell, Strain gauge type with 0-50 kg range
Rotameter	Engine cooling 40-400 LPH, Calorimeter 25-250 LPH

*The engine power of 5 kW -1800 RPM is correct as per the manufacturer specifications (Kirloskar make). The working range during testing spanned 0–100 % load in increments of 25 %, with torque varying from 0 to 26.5 Nm.

2.3. Experimental Set-up

The studies were conducted using a single-cylinder, four-stroke diesel engine coupled with an eddy current dynamometer. It is outfitted with the requisite instrumentation to measure combustion pressure and crankshaft angle. The engine indicator transmits these signals to the computer for P and PV diagrams. Alongside airflow, metrics for fuel flow, temperature, and load are supplied. The panel box contains an airbox, a petrol tank equipped with fuel flow sensors, a manometer, flow transmitters, a process indicator and an engine indicator. Rotameters are employed to quantify the flow of cooling water and calorimetric water. This configuration can be employed for engine performance analysis to evaluate the thermal dissipation of the brakes and the engine's BMEP and IMEP metrics. The "Engine Soft" software enables online evaluation of a vehicle's engine performance. A computerised measurement of Diesel injection pressure is available as an optional feature. The engine block schematic is illustrated in Fig. 2, and the engine specifications are presented in Table 1. The emissions were quantified by an AVL Hg 540 exhaust gas analyser. An AVL smoke meter was employed to assess the opacity of the smoke. The air flow rate was measured using a calibrated orifice meter connected to the engine intake manifold. This setup, integrated with a manometer, allowed precise measurement of airflow. The orifice meter was calibrated prior to experiments to ensure accuracy, adhering to standard practices for engine testing.

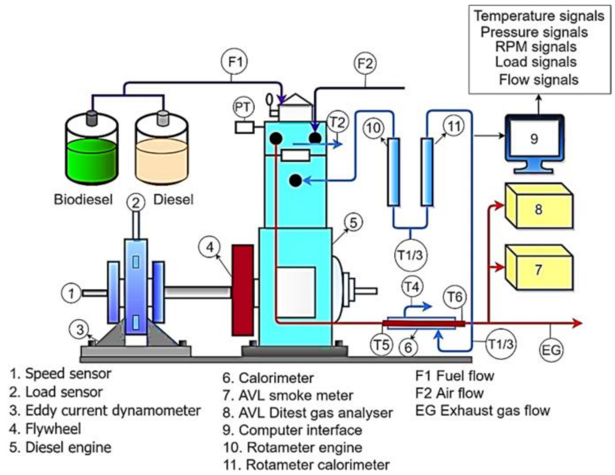

Fig. 2 Test Engine set-up block diagram

Injection timing was fixed at the manufacturer's default setting (23 ° before top dead center) to maintain consistency with conventional diesel operation. Adjusting injection timing for optimized combustion phasing is a valuable suggestion and will be explored in future studies.

All tests were conducted at a constant speed of 1800 RPM (as specified in Table 1). Load was varied from 25 % to 100 % (25 %, 50 %, 75 %, 100 %) using the eddy current dynamometer. The load increments were maintained for 10 minutes at each level to ensure thermal stabilization.

2.4. Uncertainty analysis

Table 2 contains the estimated percentage uncertainty and accuracy for BTE, BSFC, and emissions.

Tab. 2 Uncertainty and accuracy of parameters

Measured Parameter	Uncertainty (%)	Accuracy
BTE	0.90	±0.25 %
BSFC	0.93	±0.015 KG/kWh
CO	0.46	±0.06 %
NO_x	0.54	±5 ppm
HC	0.62	± 15 ppm

The overall uncertainty was estimated as 1.60 % using the following equation.

$$\text{Uncertanity}(\%) = \\ = \sqrt{(\Delta BTE)^2 + (\Delta BSFC)^2 + (\Delta CO)^2 + (\Delta NO_x)^2 + (\Delta HC)^2}$$

ΔBTE=0.90 %, ΔBSFC=0.93 %, ΔCO=0.46 %, ΔNOx=0.54 %, ΔNOx=0.54 %, and ΔHC=0.62 %

Calibration certificates for all instruments by AVL gas analyzer.

3. Results and discussion

This section examines studies of neem biodiesel blends, along with the emissions and performance of compression-ignition engines. In all instances, studies were conducted at a constant speed with varying workloads. All trials were conducted under identical conditions. The subsequent sections analyse fuel consumption, braking thermal efficiency, and emissions, including carbon dioxide, carbon monoxide, hydrocarbons, and smoke opacity, all in relation to load.

Fuel blends (B10, B15, B20) were pre-mixed before testing to ensure homogeneity. The blends were stored in sealed containers and agitated before use. Fuel composition was verified via gas chromatography (GC) to confirm biodiesel-to-diesel ratios. Continuous mixing during testing was not performed, as pre-mixed blends were stable.

3.1. Performance parameters

3.1.1 Brake thermal efficiency

Figure 3 illustrates that the thermal efficiency of the brakes increases with the escalation of engine load for diesel, B10, B15, and B20 blends. A brake thermal efficiency of 27.73 percent was attained with the B15 blend at full load. The B15 blend achieved a maximum brake thermal efficiency of 27.73 % at full load, with an average efficiency of 18.49 % across all tested loads Augmenting the oxygen concentration in neem mixtures results in incomplete combustion, hence enhancing the efficiency of all combinations. In comparison to blend B15, the heightened viscosity of the B20 combination influences thermal brake efficiency across all loads. Blend B20 exhibited inadequate atomisation and incomplete combustion.

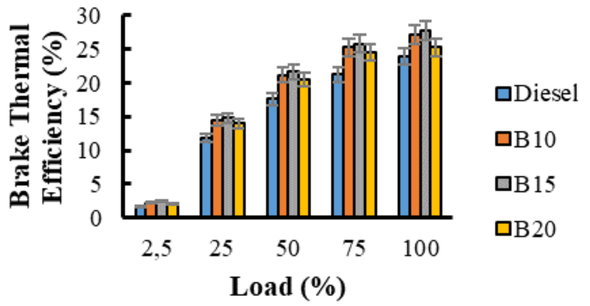

Fig. 3 Brake thermal efficiency as a function of load

3.1.2 Brake specific fuel consumption

Brake-specific fuel consumption (BSFC) quantifies the amount of petrol required to generate one pound of braking force. At reduced loads, all fuel combinations, including diesel, necessitate greater energy to generate an equivalent power output. In diesel and B10, B15, and B20 blends, brake-specific fuel consumption diminishes with increasing engine load (Fig. 4). At full load, the Brake Specific Fuel Consumption (BSFC) for B15 and B20 blends exceeds that of B10 and diesel.

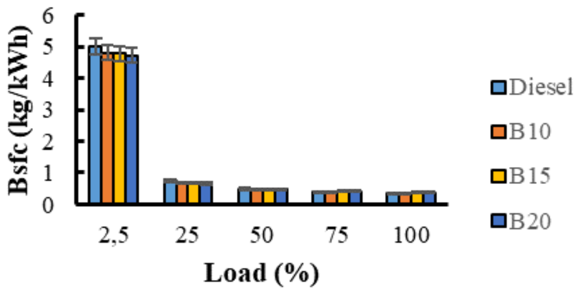

Fig. 4 Brake specific fuel consumption as a function of load

3.2. Emission parameters

3.2.1 Hydrocarbon (HC)

Figure 5 illustrates the production of hydrocarbon emissions (HC) resulting from incomplete fuel combustion. As the load escalates, oxygen availability decreases, resulting in heightened hydrocarbon emissions. Neem-based biodiesel blends have superior environmental benefits compared to diesel across all loads. The mean decrease in HC levels from diesel was 26.77 percent, 8.63 percent, and 5.75 percent for B10, B15, and B20 blends, respectively. Incorporating more neem into diesel has been shown to elevate the content of hydrocarbons (HC). As the viscosity of a combination escalates, inadequate atomisation and an ignition delay ensue.

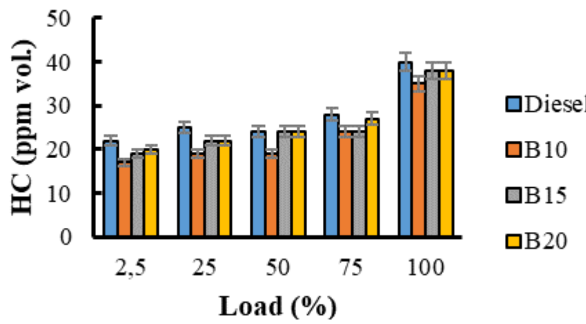

Fig. 5 Hydrocarbon emissions as a function of load

3.2.2 Carbon monoxide (CO)

Figure 6 illustrates the correlation between carbon monoxide (CO) emissions and load resulting from inefficient combustion. Under elevated loads, the oxidation process remains incomplete, resulting in increased CO emissions for diesel and B10, B15, and B20 neem mixes. The average reduction in CO emissions for B10, B15, and B20 blends compared to diesel is 32.58 percent, 24.71 percent, and 18.66 percent, respectively.

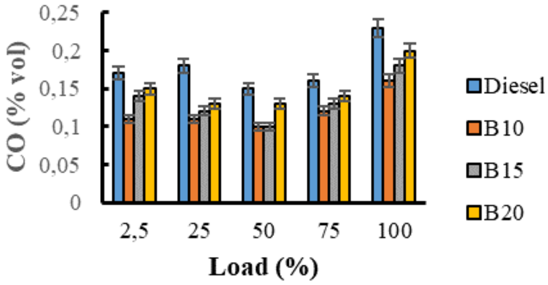

Fig. 6 Carbon monoxide emissions as a function of load

3.2.3 NO_x Emissions

Nitrogen oxides (NO_x) escalate with the augmentation of engine workload, as illustrated in Fig. 7. The biodiesel blends B10, B15, and B20 demonstrate a comparable tendency. Neem mixes augment the oxygen content in the mixture relative to diesel alone. The temperature escalates owing to the heightened oxygen content during the burning of fuel and air. Nitrogen oxides are produced in the atmosphere when nitrogen and oxygen combine at elevated temperatures. The affluent fuel-air mixture elevates the engine's temperature as the load intensifies. Nitrogen oxide concentrations increased due to heightened engine loads. NO_x emissions for B10, B15, and B20 increased by 24.56 %, 34.68 %, and 41.16 %, respectively, compared to diesel, due to elevated combustion temperatures from oxygen-rich biodiesel.

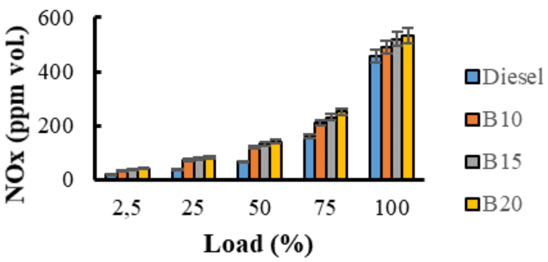

Fig. 7 Nitrogen oxide emissions as a function of load

3.2.4 Smoke Opacity (%)

The opacity of diesel and all neem mixtures escalates with increasing engine load, as illustrated in Fig. 8. Under substantial load, the engine necessitates increased fuel for combustion, leading to incomplete burning. Irrespective of the neem mixture employed, the smoke became increasingly opaque as engine load intensified. Compared to diesel, the average smoke intensity of B10, B15, and B20 blends is reduced by 19.11 percent, 27.94 percent, and 38.23 percent, respectively. Neem-based biodiesel, due to their oxygen content, generates less opaque smoke compared to pure diesel.

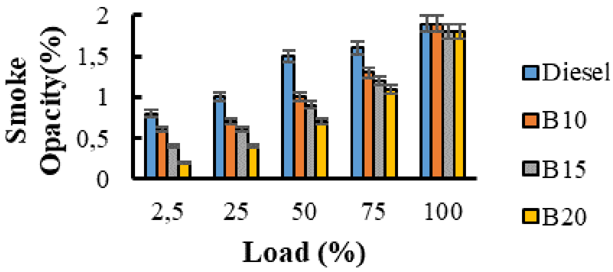

Fig. 8 Smoke opacity as a function of load

4. Conclusions

A two-step transesterification process was employed to convert neem oil into biodiesel. The initial phase is facilitated by an acid, while the subsequent phase is driven by a base. Three distinct neem-based biodiesel blends were formulated and evaluated on a single-cylinder diesel engine under varying loads and constant speed. For diesel and all blends, the brake thermal efficiency improved with increasing engine load. The B15 blend exhibits the highest brake thermal efficiency (27.73 percent) among all blends at full load. Brake-specific fuel consumption for diesel and its blends increases with rising engine load. In comparison to B10, B15, and B20 diesel fuels, the full-load consumption of brake-specific fuel increased. Hydrocarbon emissions from diesel and other blends escalate with increasing load. Diesel has elevated brake-specific fuel consumption relative to various petrol blends across all loads. Diesel fuel produces more hydrocarbon emissions than neem-based biodiesel blends. The hydrocarbon levels in B10, B15, and B20 blends were 26.77 % lower than those in diesel. Carbon monoxide emissions increase with engine load in diesel, B10, B15, and B20 blends. Carbon monoxide emissions were reduced in all blends compared to diesel. Diesel carbon monoxide emissions were reduced by 32.58 percent, 24.71 percent, and 18.66 percent for B10, B15, and B20 blends, respectively. A study indicates that augmenting the load on diesel and mixed engines elevates NO_x levels. In comparison to pure diesel, average NO_x emissions increased by 24.56 percent for B10, 34.68 percent for B15, and 41.16 percent for B20. As the engine load intensified, the opacity of the smoke from diesel, B10, B15, and B20 blends escalated. In comparison to diesel, the average smoke intensity for B10 blends decreased by 19.11 percent, for B15 blends by 27-94 percent, and for B20 blends by 38 percent.

Abbreviations

BTE	**Brake Thermal Efficiency**
BSFC	**Brake Specific Fuel Consumption**
B10	**10 % neem biodiesel + 90 % diesel (v/v)**
B15	**15 % neem biodiesel + 85 % diesel (v/v)**
B20	**20 % neem biodiesel + 85 % diesel (v/v)**

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