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EXPERIMENTAL INVESTIGATIONS ON THE PERFORMANCE AND EMISSIONS OF COMPRESSION IGNITION ENGINE FUELLED WITH LOWER BLENDS OF NEEM-BASED BIODIESEL

DINESH Y DHANDE[1], SHIRISH J NAVALE[2]

Abstract

Biodiesel has attracted a lot of attention as a possible replacement for traditional fuels due to the limited supply of fossil fuels and the growing concern about emissions of greenhouse gases. It is renewable and produces less hazardous emissions when burned. Enhancing biodiesel production is imperative to meet the escalating demand for eco-friendly fuels, serving as a remedy for the rising costs and dwindling accessibility of petroleum. This study aims in boosting neem biodiesel production specially in dry and unproductive soil regions and improving engine power using neem oil biodiesel, especially using lower blends. This study is in line with the initiatives that promote sustainable energy growth by gradually increase biodiesel blending from 15% to 30% in the near future. This research delves into the manufacturing of biodiesel from neem seeds and impact of its blends on the efficiency and emissions of compression ignition engines when combined with regular fuel. The biodiesel was produced using the transesterification method. Three distinct blends, B10, B15, and B20, were prepared by blending neem biodiesel with regular diesel. When testing engine performance, these mixtures were compared against pure diesel fuel. The specific fuel consumption and brake thermal efficiency of all blend combinations improved with increasing load. In comparison to pure diesel, there were also decreased percentages of hydrocarbons (HC), carbon monoxide (CO), and smoke opacity. There was an increase in nitrogen oxides with increasing load for all mixes as compared to pure diesel. The research results highlight neem biodiesel as a practical

[1] Department of Mechanical Engineering, AISSMS College of Engineering, Pune-411001, India, e-mail: dydhande@aissmscoe.com

[2] Department of Mechanical Engineering, AISSMS College of Engineering, Pune-411001, India, e-mail:sjnavale@aissmscoe.com

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and efficient alternative to conventional diesel fuel due to its ability to enhance engine efficiency and lowering emissions.

Keywords: alternative fuels; biodiesel production; diesel engine performance; emissions; neem biodiesel

1. Introduction

The development of society has always relied on energy. Fossil fuel extraction has always been an unsustainable and environmentally destructive practice. The global energy crisis adversely affects many poor and emerging nations. Researchers are developing sustainable energy resources to lower dependency on fossil fuels, which has two benefits: first, pollution caused by burning fossil fuels is reduced, and second, fossil fuels are preserved for future generations. Biofuel is one of the components of this expansion [7]. Non-conventional fuel sources have been sought due to stringent regulations, increased pollution, and rising fuel prices. Biodiesel manufacturing has become a significant emphasis in recent years due to escalating environmental and energy issues. Due to the implementation of biodiesel blending regulations in various countries, there has been a notable increase in the demand for biodiesel [9]. Unlike fossil fuels, biodiesel is renewable, biodegradable, and emits lower emissions. As the biodiesel is derived from plants, it helps reduce carbon and sulphide dioxide emissions when compared to traditional diesel, making it a more environmentally friendly choice. Because of its greater flashpoint, it is safer to carry and store. Because of its lubricating characteristics, it prolongs the life of engines. Thus, biodiesel is becoming increasingly popular as a transportation fuel in many nations, especially those where environmental issues and energy security are of significant importance. Vegetable and animal oils have been extensively utilised in the production of biodiesel. There is a rising interest in utilising waste fats of animal origin for the production of biodiesel. In India, Jatropha is the most common feedstock; however, its production is three times more expensive than that of pure diesel [28].

Alternative options considered in the study included pongamia, mahua, sunflower,neem oil, koroch and animal fats, alongside cottonseed, as well as soybean crude oil and rapeseed oil. Tallow methyl esters, palm, waste cooking oil, and kopak methyl ester were also taken into account [13, 27, 18]. Haşimoğlu et al. [10] employed the low heat rejection (LHR) engine concept by transforming a turbocharged direct injection (DI) diesel engine into a low heat rejection engine. They conducted tests on the performance of sunflower oil biodiesel and observed enhancements in specific fuel consumption and brake thermal efficiency. The exploration of a diverse range of non-edible oils, including madhuca indica (mahua), jatropha curcas (ratan jyoti), and melia azadirachta (neem), was undertaken by Khandelwal et al. [14]. These oils were found to be more cost-effective than edible oils in biodiesel manufacturing. Aspects

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such as oilseeds from trees, oil extraction methods, and biodiesel production technologies were covered in the study. Wild mustard oil as a biodiesel source was investigated by Jham et al. [11]. Biodiesel with a concentration of 94% by weight was produced through the trans-esterification of methanol with a sodium methoxide catalyst. Fuel blends containing 5%, 10%, and 20% citrus sinensis biodiesel with conventional diesel were evaluated by Serin et al. [28]. The performance and exhaust emissions of the blended biodiesel were found to be identical to pure biodiesel. The use of citrus sinensis biodiesel had only a minor impact on power and torque but increased NOx emissions while decreasing CO. Solaimuthu et al. [30] conducted a study on engine performance and emissions by testing mahua biodiesel and different fuel blends in a single-cylinder diesel engine. The researchers utilized a combination of selective catalytic reduction (SCR), cold exhaust gas recirculation, and hot exhaust gas recirculation to mitigate NOx emissions. The outcomes were noteworthy, projecting a 20% reduction in NOx emissions for engines running on pure biodiesel fuel and employing SCR technology. Özener et al. [23] investigated the combustion, performance, and emission characteristics of biodiesel derived from soybean oil and its blends in a single-cylinder diesel engine. They observed a noteworthy decrease in carbon monoxide and unburned total hydrocarbons, although there was a slight increase in nitric oxides and carbon dioxide emissions. Baweja et al. [5] and Prajapati [24] examined the performance and emissions of a compression ignition (CI) engine fueled with different blends of mustard oil biodiesel. The study revealed that a 10% blending of mustard oil biodiesel demonstrated optimal performance, particularly at an 80% load. The biofuel production potential of waste rice and neem seeds through fermentation and transesterification was explored by Reang et al. [26] The enhancement of engine performance, including notable improvements in brake thermal efficiency and reduced fuel consumption compared to diesel, was demonstrated through the addition of 5% rice wine alcohol to a neem methyl ester-diesel blend. However, an observed increase in nitrogen oxide emissions underscores the environmental trade-offs associated with these biofuel blends.

Knothe et al. [16] noticed that the fatty esters in biodiesel have a direct impact on its properties. A combination of fat and alcohol moieties can affect the cetane number, cold flow rate, stability, viscosity, and lubricity. Increased chain length and unsaturation improve the cetane number, melting point, and viscosity of plain fatty substances. Isopropyl esters appear to outperform methyl esters when it comes to fuel characteristics. Isopropanol is costlier than methanol, and transesterification is necessary to make it worthwhile. To produce fuel-quality biodiesel, Canakci et al. [6] studied low-cost, high-FFA feedstock. High FFA feedstock could not be processed using conventional alkali catalysed transesterification methods. This occurs when alkaline catalysts react with fatty acid esters (FAEs). Soap acts as a catalyst in this process, preventing the separation of glycerine and ester. Triglycerides were converted using an acid catalyst that reduced the FFA content of high FFA feedstock to less than 1%. To imitate a high FFA feedstock, soybean oil with less than 20% palmitic acid was used in the experiment. According to the study, acid- catalysed pre-treatment might lower the feedstock's FFA concentration to less than 1%. Acid catalysts and methanol were needed

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for yellow and brown grease. Mathiyazhagan et al. [19] studied non-edible oils as a biodiesel feedstock. The alkali-catalysed process was used to produce biodiesel.

It is impossible to trans esterify non-edible oils with high FFA concentrations. Biodiesel was created using two-step catalysts. Non-food oils containing FFA were widely available for the manufacturing of biodiesel fuel. Ma and Hanna [17] carried out a comprehensive review on diverse methods of biodiesel production from used cooking oil, encompassing direct use and blending, micro-emulsions, thermal cracking (pyrolysis), and transesterification. The transesterification process, commonly employed, offers advantages owing to its cost-effectiveness in production and the economic recovery of glycerol, a by-product of biodiesel.

Neem is an excellent non-edible biodiesel feedstock because of its wide range of uses. It may live for roughly ninety years on average and is readily available. It can grow practically everywhere. After five years of development, it begins to consistently produce fruit. Dhar et al. [8] attempted to produce biodiesel from neem oil. Moisture and free fatty acid (FFA) levels affect the output and quality of biodiesel. The esterification and transesterification procedures were utilised to produce biodiesel. The performance of the blends was evaluated using a DI diesel engine. In terms of fuel economy and thermal efficiency, biodiesel and its blends exceed mineral diesel. While biodiesel increased NOx emissions, it decreased HC and CO emissions. when compared to mineral diesel. Balaji and Cheralathan [3] explored the impact of an antioxidant additive (Butylated hydroxytoluene) on oxidation stability and NOx emissions in a direct injection diesel engine fuelled by methyl ester of neem oil. The findings indicate that the antioxidant additive effectively enhances the oxidation stability and helps regulate the NOx emissions of diesel engines fuelled by methyl ester of neem oil.

Thangaraj et al. [31] devised a two-step reaction technique for the production of biodiesel from neem seeds. The use of a short-chain alcohol such as methanol allowed for the measurement of the biodiesel's kinematic viscosity, density, and flashpoint. Ali et al. [1] studied the characteristics of neem oil-based biodiesel production and the fuel properties of neem biodiesel blends. They found that if neem oil planting and harvesting were performed regularly, biodiesel production might minimise the need for diesel fuel imports. Radha et al. [25] investigated biodiesel generation from neem oil. The biodiesel generated by transesterification had the highest yields, and the most influential experimental conditions were discovered. Biodiesel was produced at various temperatures and molar ratios of oil to alcohol. Using biodiesel as a diesel fuel resulted in reduced smoke and CO emissions. In contrast to this, NOx emissions remained steady.

Low volatility and polyunsaturated nature have affected triglyceride replacement for diesel, according to Mustafa Balat and Havva Balat [4]. The most prevalent technique of creating biodiesel is transesterification, which produces mono alkyl esters of vegetable oils and fats. Transesterification is affected by temperature, pressure, and time, as well as the molecular weight of the alcohol-to-glyceride transition. In diesel engines, biodiesel generated from

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neem seed and camelina sativa was evaluated for emissions and performance. In the engine, fuel methyl esters derived from neem and camelina sativa oils were tried. A 1.9-liter litre multi-cylinder diesel engine was used to assess engine performance. At all engine speeds tested, BP and BSFC were considerably different between CB10 biodiesel and diesel. CB10 biodiesel offers lower average emissions than other biodiesel fuels, which helps to minimise pollution and protect the environment. In unaltered engines, diesel fuel can be replaced with CB10. Nair et al. [22] investigated Neem oil biodiesel blends' emission and performance characteristics in a diesel engine. Prepared through transesterification with 1% v/v sulphuric acid, B10 blend demonstrated lower emissions and higher performance compared to other blends and diesel. Brake thermal efficiency exceeded diesel, with CO, HC, and NOX emissions lower than diesel. S. Siluvaimuthu [29] studied enhancing the performance of a NO–WGO mix employing lower- and higher-order alcohols in terms of engine performance, emissions, and combustion characteristics. The effects of injecting and combining alcohol with NO and WGO mixtures were examined at different loads. When compared to fuel blends, alcohol injection resulted in higher NOx emissions.

Mu et al [21] investigated the performance and emission characteristics of a diesel engine with varying ratios of tung oil-based biodiesel blends and neat diesel under different operating conditions. The experimental results showed that the addition of biodiesel blends had different effects on engine power and torque depending on the blend ratio.

Recently, the performance and emission characteristics of neem oil biodiesel blended at 20% with pure diesel were studied by Kannan et al. [12]. Improved performance and emissions were observed, except for NOx. The performance and emissions of a diesel engine powered with quaternary blends were investigated by Khan et al. [15]. The results demonstrate that the blend with the least decanol content significantly reduced carbon monoxide (CO) and un-burnt hydrocarbon (UHC) emissions compared to diesel. Additionally, the blend containing 45% decanol exhibited the lowest nitrogen oxide (NOx) and smoke concentrations, while achieving the lowest brake-specific fuel consumption at 500 bar and 20 Nm, albeit with a 3.22% increase compared to diesel, and the highest brake thermal efficiency at the same injection pressure and load, albeit 3.26% lower than pure diesel.

In an experimental study conducted by Ali et al. [2], the comparative impact on cold flow parameters of biodiesel produced from Azadirachta indica (Neem oil) through blending with petroleum-based fuels and natural organic solvents was investigated. It is recommended that blended mixed kerosene/diesel and a biodiesel blend with turpentine oil be used in diesel engines, ensuring suitable physico-chemical and cold flow properties.

A review of the literature demonstrates limited research on the performance of lower blends of neem-based biodiesel as a fuel for diesel engines. Considering the rising demand for biodiesel and the scarcity and cost of petroleum products, there is an increasing need for diverse biodiesel sources. The neem tree, known for its ability to thrive in dry and infertile

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soil, emerges as a promising biodiesel resource. It has been estimated that Indian neem trees yield approximately 3.5 million tons of kernels annually, with the potential to recover around 700,000 tons. In the year 1990, India exported about 34 tons of neem seeds. The neem plant is characterized by its rapid growth, boasting a long productive life span of 150–200 years. It demonstrates resilience by thriving in drought-prone and nutrient-poor soils, enduring temperatures ranging from a 44°C to 4°C. Notably, the neem plant is distinguished by its high oil content, ranging from (39.7–60)%. A mature neem tree yields an annual harvest of (30–50) kg of fruit.

This study aims to establish a benchmark by promoting the larger-scale production of neem biodiesel for lower blends, aligning with government policies such as India's guidelines on biodiesel blending up to (15–30)% in the future. The study involved the production of neem oil biodiesel from neem seeds and experimental evaluation of various blends on a single-cylinder diesel engine to assess the performance and emissions. The obtained results were compared with those from an engine fuelled exclusively with pure diesel.

2. Materials and Methodology

Biodiesel Preparation

Initially, one litre of neem oil was gently heated to 100°C for five minutes in three-necked glass flasks, ensuring the removal of any water content. To determine the acid value, a solution of 0.1 N KOH in distilled water was carefully prepared and positioned in the measuring burette. Subsequently, phenolphthalein indicator was delicately introduced to 10 ml of neem oil, followed by the addition of methyl alcohol to create the solvent for analysis. The acid value was meticulously determined by titrating the solution until the solvent delicately turned pink, resulting in an observed acidity level of 5 mg KOH/g. The subsequent execution of the two-step processes of esterification and transesterification followed. For the esterification of neem oil, the acid catalyst H2SO4 was thoughtfully employed. At 55°C, a one percent H2SO4 acid catalyst was measured in 160 ml of methanol and gently added to 1000 ml of neem oil. The mixture was stirred at a temperature of 60°C for sixty minutes, delicately reducing the viscosity and acidity of neem oil through the acid esterification reaction. In the subsequent step, the esterified oil mixture was carefully separated from methanol, acid, and impurities resulting from the acid esterification reaction.

The transesterification process delicately involved the reaction of oil triglycerides with methanol, utilising a 1% KOH base catalyst at 55°C. The reaction was gently sustained for sixty minutes at 60°C and at a speed of 300 rpm stirring. The transesterification solution was tenderly permitted to settle in a conical flask for twelve hours to facilitate the gentle separation of biodiesel and glycerol. For water washing, 100 ml of oil and 100 ml of distilled

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water were thoughtfully employed to delicately eliminate methanol and other impurities. The dehydration of the biodiesel was meticulously executed to ensure its highest quality. Ultimately, a refined 750 ml of neem oil biodiesel was derived from the initial 1000 ml of raw neem oil. Table 1 list various properties of neem oil, neem oil biodiesel and conventional diesel.

Tab. 1. Various properties of neem oil, neem oil biodiesel and conventional diesel

Property	Neem oil	Neem oil biodiesel	Diesel
Density, g/cm^3	0.88	0.778	0.84
Calorific Value, kJ/kg	27500	40500	45000
Cetane value	39	54	49
Kinematic viscosity at 40°C, cSt	30.10	4.85	3.75
Flash point, °C	300	160	60

Figure 1 depicts the various stages of neem biodiesel synthesis.

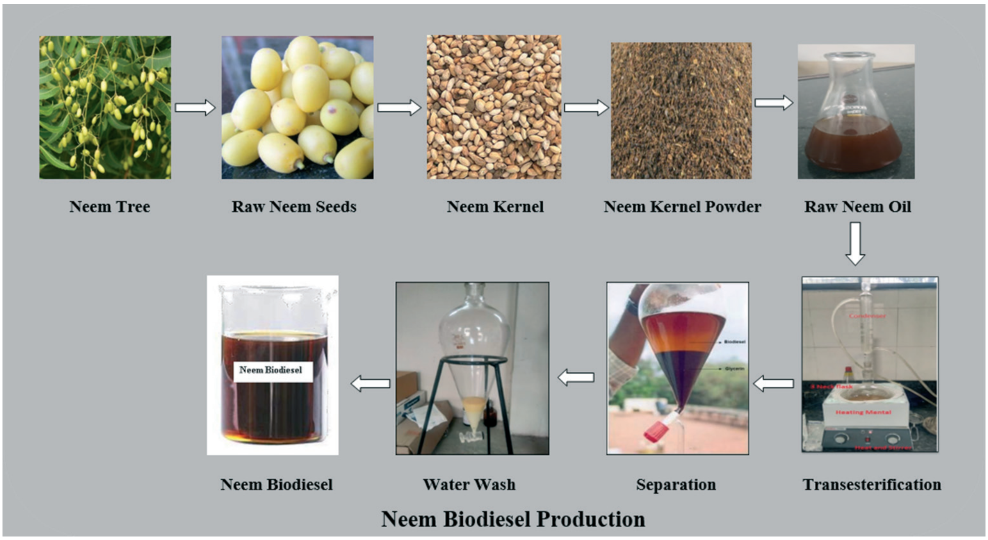

Fig. 1. Steps involved in neem biodiesel production process

Experimental Set-up

The experiments were performed with a single-cylinder, four-stroke diesel engine loaded by an eddy current dynamometer. It is equipped with the necessary instruments to detect combustion pressure and crankshaft angle. For plotting pressure-crank angle (P-θ) and pres-

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sure-volume (P-V) diagrams, the engine sensor sends these signals to the computer. In addition to airflow, measures of fuel flow, temperature, and load are provided. It has a panel box that houses an air box, a fuel tank with fuel flow sensors as well as a manometer and flow transmitters, a process indication, and an engine indicator. Rotameters are used to measure the flow of cooling water and calorimeter water. This arrangement can be utilised for engine performance research to assess the heat dissipation of the brakes as well as the power of the engine's BMEP and IMEP readings. The engine was fuelled with prepared blends of neem biodiesel. The tests were carried out at constant speed and loads. The "Engine Soft" software was used to record a vehicle's engine performance online. A computerised measurement of diesel injection pressure is provided. The fuel consumption and mass flow rate of fuel was measured using a sensor and data acquisition system. The engine block diagram is shown in Figure 2, and the engine specifications are listed in Table 2.

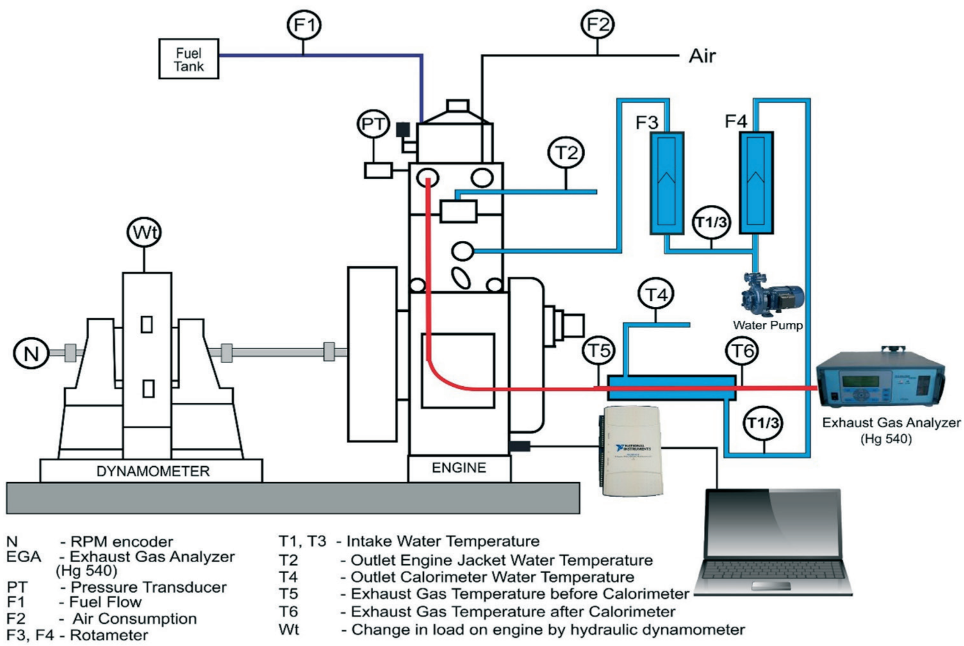

Fig. 2. Test engine set-up block diagram

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Tab. 2. Test Engine Specifications

Engine Parameter	Specifications
Make	Kirloskar, TV1
Engine	Water-cooled, single-cylinder, four-stroke diesel engine with a power of 5.2 kW at 1500 rpm
Stroke × Bore (mm)	110 × 85.5
Cylinder capacity (cm^3)	661
Compression Ratio	17
Dynamometer	Type eddy current, water-cooled
Calorimeter	Type pipe in pipe
Piezo sensor	Range 5000 PSI with low noise cable
Crank angle sensor	Resolution 1 degree, Speed 5500 with TDC pulse
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
Fuel flow transmitter	DP transmitter with range (0–500) mm of water column
Air Flow transmitter	Pressure transmitter, Range (-) 250 mm of water column

The emissions were measured using an AVL 444 DiGas, five channel, exhaust gas analyser shown in Figure 3. It was equipped with an exhaust gas inlet, which was placed in the exhaust gas pipe. The warm up time was provided for seven minutes. An exhaust gas inlet was put in the exhaust pipe. Hydrocarbons, Cabon monoxide and nitrogen oxides were measured and noted during testing.

Fig. 3. AVL 444 DiGas exhaust gas analyser

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An AVL 437C smoke meter, shown in Figure 4, was used to measure the opacity of the smoke. The device evaluates air pollution by measuring fluorescence emission characteristics. It employs shields around light sources and cells to minimize light interference, ensuring accurate readings. The chamber's dimensions are tightly controlled within a range of 0.430 m ± 0.005 m. To prevent light differentiation, matte black light traps are used to absorb reflections and diffuse light. The light source operates within a temperature range of (2800–3250) K, emitting incandescent colour, while a photocell detects emitted light. The device's electrical circuit demonstrates a reaction time between 0.9 seconds and 1.1 seconds, with the indicator reaching 90% of full scale. Temperature regulation within the measuring chamber, maintained at 100°C ± 5°C, is ensured by a dedicated temperature sensor connected to the regulator.

Fig. 4. AVL 437C Smoke meter

The specifications of the gas analyser and smoke meter are listed in Table 3.

Tab. 3. Gas Analyser and Smoke Meter Specifications

Emission	Range	Accuracy	% Error
Gas Analyser Specifications:			
HC	(0–20000) ppm	+ 10 ppm	± 1 ppm
CO	(0–10)% v/v	+ 0.01% v/v	± 0.01% v/v
NOx	(0–5000) ppm	+ 10 ppm	± 1 ppm
Smoke Meter Specifications:			
Smoke intensity	(0–100) BSN	+ 1% BSN	± 2 BSN

Uncertainty Analysis

The systematic methods for computing error estimates for experimental data are part of uncertainty analysis. It is typically believed that data is gathered under fixed operating conditions and that a thorough understanding of all system components is available when evaluating errors in IC engine tests. The following equation is used to determine the uncertainty propagation for parameters for which the evaluation depends on two or more independent parameters:

$$\frac{U_y}{y}=\sqrt{\left(\frac{u_{x1}}{x_1}\right)^2+\left(\frac{u_{x1}}{x_1}\right)^2 ....+\left(\frac{u_{x1}}{x_1}\right)^2} \tag{1}$$

where u_x and u_y, respectively, represent uncertainty and testing values for the assessed parameters x_1, x_2,….., xn. The uncertainty analysis presented in Table 4 is based on a technique proposed by Moffat [20]. The analysis only takes into account measurement-related errors for experimental measurements.

Tab. 4. Uncertainty and accuracy of measured parameters

Measured Parameter	Accuracy	Uncertainty at Maximum Load [%]	Uncertainty at Minimum Load [%]
BTE	± 2 %	± 0.2	± 4.144
BSFC	± 2 %	± 1.5	± 4.144
CO	± 0.02% v/v	± 0.1	--
NOx	± 20 ppm	± 0.2	--
HC	± 10 ppm	± 0.1	--

The overall uncertainty is estimated at maximum and minimum load using the following equation:

$$\text{Uncertanity (\%) (At max.load)} =\sqrt{(\Delta BTE)^2+(\Delta BSFC)^2+(\Delta CO)^2+(\Delta NO_x)^2+(\Delta HC)^2} =3.278\% \tag{2}$$

$$\text{Uncertanity (\%) (At min.load)} =\sqrt{(\Delta BTE)^2+(\Delta BSFC)^2+(\Delta CO)^2+(\Delta NO_x)^2+(\Delta HC)^2} =5.86\% \tag{3}$$

Where ΔBTE, ΔBSFC, ΔCO, ΔNOx and ΔHC represent uncertainty in brake thermal efficiency, brake specific fuel consumption, carbon monoxide, nitrogen oxide and hydrocarbon respectively. The lower values of uncertainty at maximum as well as low load value proves that the measurements are accurate. But there will be some uncertainty exists in the measurements.

3. Results and Discussion

This section discusses the performance and emissions of compression ignition engine when fuelled with various blends of neem biodiesel. Three blends (B10, B15 and B20) were prepared in the proportion of 10%, 15% and 20% of biodiesel blending with conventional diesel on volumetric basis (% v/v). Each blend was tested at constant speed and the load was varied from

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2.5 percent to full load. The load values were 0.54 kg (2.5%), 3.13 kg (25%), 6.20 kg (50%), 9.04 kg (75%) and 11.96 kg (100%). The engine was run on pure diesel by varying the load from 2.5% to full load at constant speed of 1500 rpm and compression ratio of 17. The engine was stopped after each test and allowed to cool for two to three hours to get correct values of next test fuel. Then, the engine was run with B10, B15 and B20 blends and its performance as well as emissions were tested. The results were recorded with the software available with the test rig. All of the experiments were performed under the identical set of circumstances.

The below sections exhibit the variation of fuel consumption, brake thermal efficiency, as well as emissions such as carbon dioxide, carbon monoxide, hydrocarbons, and smoke opacity, for the three blends and above mentioned loading conditions.

Performance Parameters

Brake thermal efficiency

The rise in brake thermal efficiency as the engine load increases for diesel as well as B10, B15, and B20 blends is depicted by Figure 5. This increase was attributed to improved combustion and reduced frictional losses at higher loads. The highest brake thermal efficiency (BTE) of 27.73% was reported for the B15 blend under full load conditions. The oxygen content and heat carrying capacity of blended fuels were enhanced with increase in blend ratio. The enrichment of oxygen content improved the viscosity and heat carrying capacity of the blends, resulting in better spray formation and atomisation, and effective combustion was observed [31]. Therefore, the highest BTE among all tested blends was shown by the B20 blend.

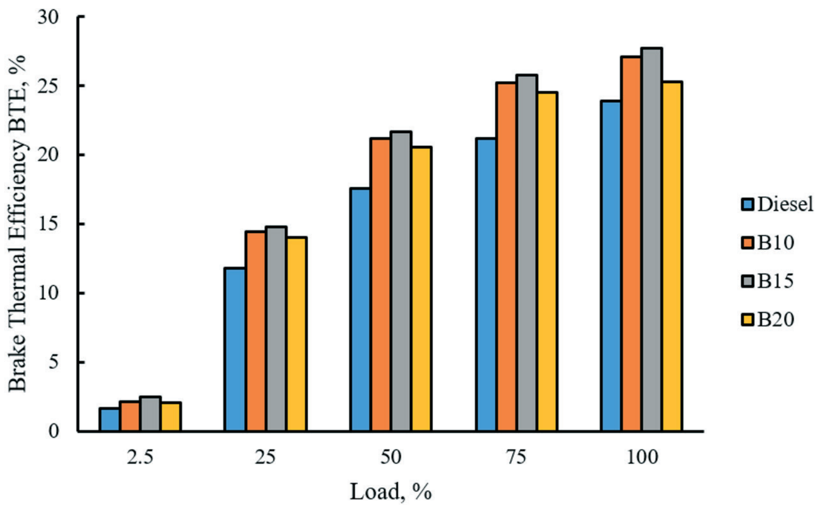

Fig. 5. Brake thermal efficiency as a function of load

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Brake specific fuel consumption

The rate of fuel quantity combusted to deliver unit power output is denoted by brake specific fuel consumption. The variation of BSFC values for all fuel samples with engine load is illustrated in Figure 6. A decrease in BSFC is observed with an increase in engine load for all tested fuels. At higher engine loads, greater cylinder temperatures were encountered, leading to improved combustion and fuel economy. The lowest BSFC was noted for B20 fuel at all engine loads due to its highest calorific value among the tested fuels, ensuring efficient combustion. Among the blends, the maximum and minimum BSFCs were observed for B10 and B20 blends, respectively. Thus, the inclusion of higher blending offers lower BSFC which results in low viscosity, density and more oxygen molecule availability to accelerate combustion.

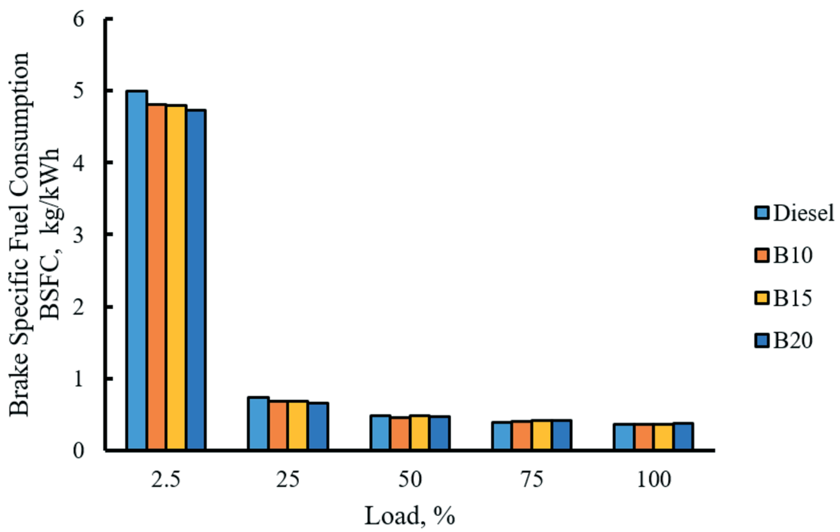

Fig. 6. Brake specific fuel consumption as a function of load

Emission parameters

Hydrocarbon (HC)

Figure 7 illustrates the hydrocarbon (HC) emission with different biodiesel mixing ratios at various loads. It is noted that the HC emission decreases with both an increase in biodiesel mixing ratio and an increase in load. This reduction is ascribed to the higher oxygen content in the biodiesel. Consequently, biodiesel blending enhances combustion in the cylinder due to proper heat distribution within the combustion cylinder. On average, a reduction in HC levels of 26.77%, 8.63%, and 5.75% for B10, B15, and B20 combinations, respectively, was observed compared to diesel.

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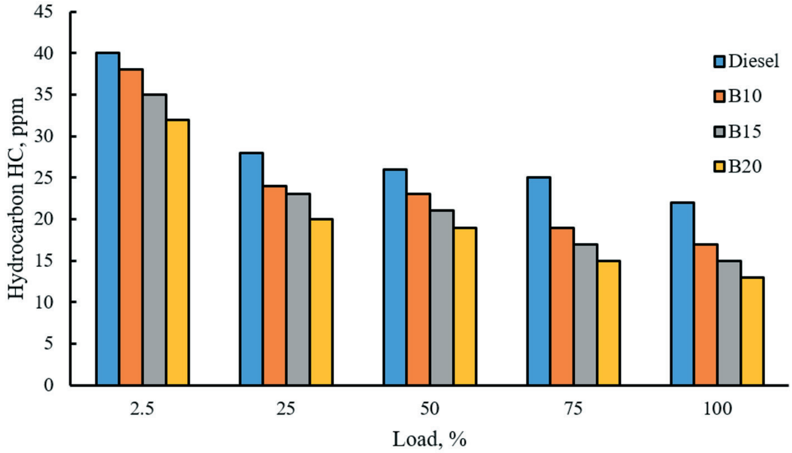

Fig. 7. Hydrocarbon emissions as a function of load

Carbon monoxide (CO)

The relationship between carbon monoxide emissions and load due to inefficient combustion is depicted in Figure 8. The CO concentration decreases with increase in load. The rise in load elevates the cylinder temperature resulting in complete combustion. The CO concentration was observed to be maximum for pure diesel for all loads. Among the blends, higher and lower CO concentrations were noticed for B20 and B10 respectively. During high loads, the oxidation process is not completed, and CO emissions for diesel and B10, B15, and B20 neem blends increase. For B10, B15, and B20 blends, the average reduction in CO emissions as compared to diesel is 32.58%, 24.71%, and 18.66%, respectively.

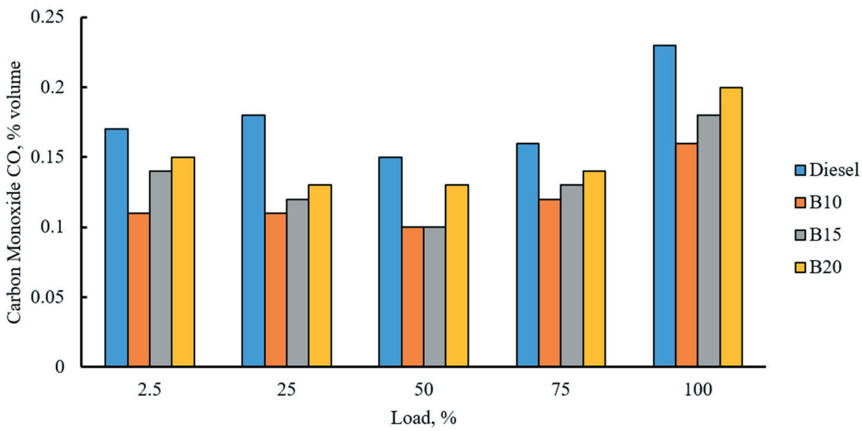

Fig. 8. Carbon monoxide emissions as a function of load

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Nitrogen oxides (NOx) Emissions

Nitrogen oxides increase as the engine load increases, as seen in Figure 9. The biodiesel blends B10, B15, and B20 exhibit a similar trend for all test loads. Neem blends increase the amount of oxygen in the mixture when compared to diesel alone. The temperature rises due to the increased oxygen concentration in the combustion of fuel and air. Nitrogen oxides are generated in the atmosphere when nitrogen and oxygen mix at high temperatures. The rich oxygen in the fuel blend causes the engine's temperature to rise as the engine's load increases. Nitrogen oxide levels rose as a result of increased engine loads. For B10, B15, and B20, the average NOx emissions rose by 24.56%, 34.68%, and 41.16% compared to pure diesel.

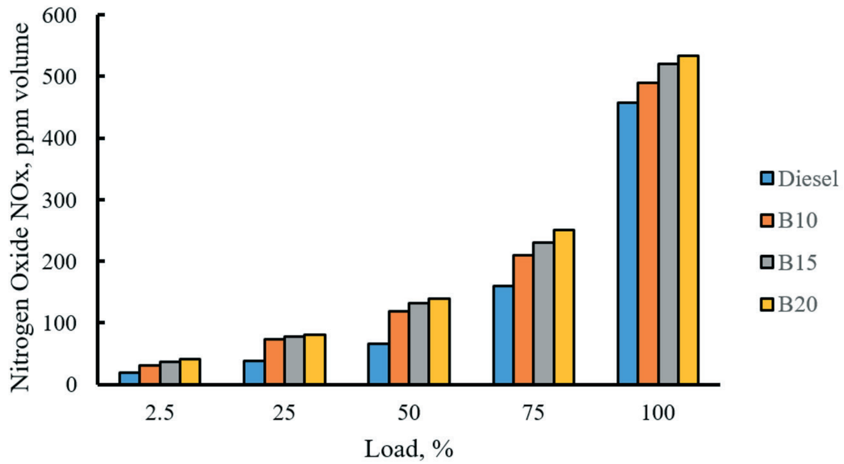

Fig. 9. Nitrogen oxide emissions as a function of load

Smoke Opacity

Opacity measurement calculates the value of particulate matter emission by diesel engines. The emission of smoke is primarily caused by incomplete combustion of the mixture, poor atomisation, spray formation, and an oxygen-deficient environment in the engine cylinder. The smoke opacity of the engine, when fuelled with diesel and all neem mixes increases as engine load increases, as seen in Figure 10. When the engine is under heavy load, more fuel is required for burning, resulting in incomplete combustion. Moreover, the high engine load resulted in an increase in the fuel droplet size, which further promoted smoke formation. Interestingly, the fuel blends resulted in lower smoke opacity than pure diesel at all engine loads. When compared to diesel, the average smoke intensity with B10, B15, and B20 blends is lowered by 19.11%, 27.94%, and 38.23%, respectively. Since the neem-based biodiesels contain oxygen in their mixes, they produce more clear smoke than pure diesel.

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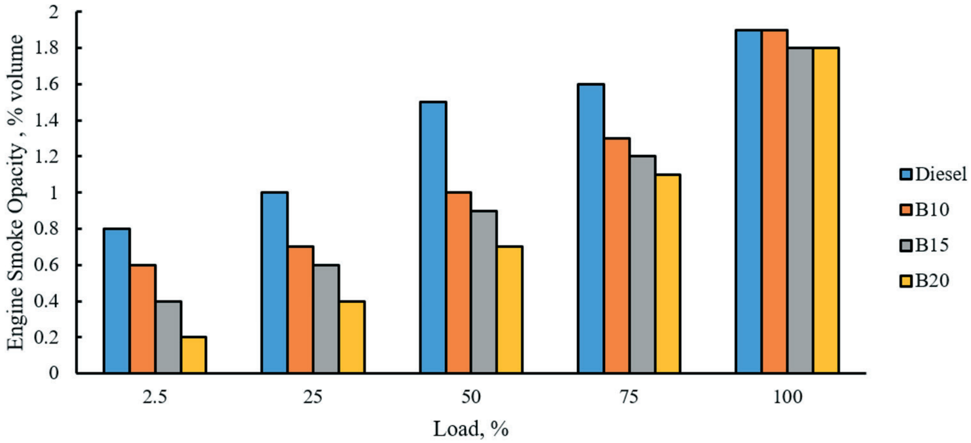

Fig. 10. Smoke opacity as a function of load

4. Conclusions

The presented work focuses on the production of neem oil biodiesel and its impact on the performance and emissions of a diesel engine under varying loads. A two-stage transesterification technique was employed to convert neem oil into biodiesel, with the first stage catalysed by acid and the second by a base. Three distinct neem-based biodiesel blends were created and evaluated on a single-cylinder diesel engine, with load variations and a constant speed. An increase in engine load for all test fuels led to a rise in brake power. When increasing the engine load from 2.5% to full load, the highest brake power was exhibited by pure diesel among all fuel samples. Beyond 75% load, all blends showed almost identical values of brake power at the highest load. In the case of diesel and all blends, the thermal efficiency of the brakes rose as the engine load increased. The B15 blend has the highest brake thermal efficiency (27.73%) of any blend at full load. The brake-specific fuel consumption for diesel and blends rose as engine load increased. When compared to B10, B15, and B20 diesel fuel, the full-load consumption of brake-specific fuel rose. Diesel has higher brake-specific fuel consumption when compared to other biodiesel mixes for all loads. The hydrocarbon emissions from diesel and all other blends decreases as the load increases. Diesel fuel yields greater hydrocarbon emissions than neem-based biodiesel mixes. The average reduction in HC levels from diesel was 26.77%, 8.63%, and 5.75% for B10, B15, and B20 combinations. Carbon monoxide emissions rise with engine load in diesel, B10, B15, and B20 mixes. Carbon monoxide emissions were lower in all blends than in diesel. Diesel CO emissions were lowered by 32.58%, 24.71%, and 18.66% for B10, B15, and B20 blends, respectively. According to the study, increasing the load on diesel and mix engines enhances NOx levels. Compared to pure diesel, average NOx emissions rose by 24.56% for B10, 34.68% for B15, and 41.16% for B20.

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As the engine load increased, the opacity of the engine smoke with diesel, B10, B15, and B20 blends increased. When compared to diesel, the average smoke intensity for B10 blends was lowered by 19.11%, (27–94)% for B15 blends, and 38% for B20 blends.

Therefore, it is concluded that the blending of neem biodiesel with pure diesel proves to be beneficial in improving performance. The enhanced oxygen content by increase in blending ratio ensures complete combustion, thereby mitigating CO, HC, and smoke emissions. The neem biodiesel blends can be readily used in modern diesel engines as a sustainable and alternate future fuel. It can be a better source of biodiesel where the soil is dry and infertile which will help in reduction of global warming effect as well as boost the economy of the nation.

5. Nomenclature

BMEP	brake mean effective pressure
BP	brake power
BSFC	brake specific fuel injection
BTE	brake thermal efficiency
CO	carbon monoxide
CO_2	carbon dioxide
DI	direct injection
FAE	fatty acid esters
FFA	free fatty acids
HC	hydrocarbons
H_2SO_4	sulphuric acid
IC	internal combustion
IMEP	indicated mean effective pressure
KOH	potassium hydroxide
NBBD	neem-based biodiesel
NO	neem oil
NOx	nitrogen oxides
SCR	selective catalytic reduction
UHC	un-burnt hydrocarbon
WGO	wintergreen oil

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Conflicts of interest/Competing interests

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Availability/ of data and material (data transparency)

All data generated or analysed during this study are included in this published article

Code availability

Not Applicable

Ethics approval

Not Applicable

Consent to participate

Not Applicable

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Author Contribution

Author	Role
D. Y. Dhande	Methodology, Formal analysis, Writing – Original Draft Validation, Visualization
S. J. Navale	Conceptualization, Investigation, Writing – Review & Editing, Project administration, Formal analysis, Resources, Supervision

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