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PRODUCTION AND PERFORMANCE ASSESSMENT OF MARULA *(Sclerocarya birrea)* BIODIESEL IN A COMPRESSION IGNITION ENGINE

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ABSTRACT

Interest in investigating less polluting, renewable, and non- petroleum fuels has increased due to rising fuel prices, environmental concerns, and the depletion of fossil oil reserves. It has been established that biodiesel serves as an effective substitute for conventional neat fuel in compression ignition (CI) engines. In this study, marula biodiesel was produced via a transesterification process employing methanol at a ratio of 6:1, with potassium hydroxide as the catalyst at a concentration of 1.4 wt%. The mixture was heated in a beaker placed on a hot plate with a magnetic stirrer for 30 minutes at a temperature of 60 °C and operated at a speed of 305.5 rpm. The most common physicochemical properties of marula biodiesel were determined in accordance with (ASTM D 6751 and EN 14214) Standards. The oil yield from the marula was determined to be 58.7%. The saponification value, iodine value, free fatty acid content, acid value, peroxide value, cetane number, density, viscosity, calorific value, flash point, and pour point for both marula oil and marula biodiesel were found to be 187.72 mg KOH/g, 61. 77 g /100 g, (1.72% and 0. 21%), (3.42 mg KOH/g and 0.44 mg KOH/g), (10.67 meq/kg and 2 meq/kg), (51 and 55.1), (943 kg/m^3 and 850kg/m^3), (41 mm^2/sec and 5. 0 mm^2/sec), (38.40 MJ/kg and 42. 89 MJ/kg), (240 °C and 175 °C), (5 °C and 3 °C), respectively. The generation and performance evaluation of marula biodiesel in a compression ignition engine under various load conditions are discussed in this experiment. At a peak load of 2500 g, both engine torque and brake power increased, with B10 producing the highest torque of 13.52 Nm. Brake specific fuel consumption decreased, with B30 demonstrating the most favorable fuel efficiency. As the load increased, brake thermal efficiency also increased, with B30 achieving the maximum efficiency among all tested fuels. Emissions of carbon monoxide (CO) and hydrocarbons (HC) decreased with increasing biodiesel content; B60 exhibited the lowest CO emissions, while B100 showed the minimum carbon dioxide (CO_2) and HC emissions. Overall, B30 provided the optimal balance between engine output and emissions control, confirming marula as a sustainable alternative fuel for compression-ignition engines.

Keywords: Marula Biodiesel, Compression Ignition Engine, Biodiesel-Diesel Blends, Brake Thermal Efficiency, Engine Performance Analysis, Exhaust Emission Characteristics

INTRODUCTION

Conventional energy sources such as coal, gas, and oil remain the predominant forms of energy consumed globally today. These resources possess limited reserves that are not anticipated to last for an extended period (Yunus & Zuru, 2017). Furthermore, greenhouse gas emissions arising from the utilization of fossil fuels significantly contribute to climate change, prompting the search for alternative energy sources to replace non-renewable options. Among these alternatives are biofuels, bio-ethanol, and bio-oil, primarily derived from biomass, which have considerably advanced the biofuel industry (Fapetu et al., 2018). Most vegetable oils serve as suitable substrates for numerous feedstocks proposed for biodiesel production (Aliyu et al., 2025). For all biodiesel fuels, property data must be available to evaluate their suitability for use in diesel engines. Despite numerous issues associated with their direct application in compression ignition (CI) engines, particularly in direct-injection engines, such problems include injector coking, poor fuel atomization, thickening of lubricating oil, carbon deposits, and injector clogging (Singh & Gu, 2010). Transesterification is a catalytic process that converts lipids into fatty ester methyl esters (FAME) and glycerol as a byproduct through four steps. The initial stage involves preparing the catalyst and mixing it with alcohol. The second stage, the transesterification reaction, occurs through interaction between the catalyst-alcohol mixture and triglycerides (fatty acids). This reaction is generally conducted within an optimal temperature range of approximately 40-60°C, where the reaction rate increases with rising temperature. The third stage entails separating glycerol from the resulting biodiesel. Finally, the fourth stage involves water washing to purify both the biodiesel and glycerol present within it.in the biodiesel (Manirafasha et al., 2020).

Used cooking oil, vegetable oil, and animal fat are triglycerides, transesterified to produce biodiesel (Azuaga et al., 2018; Chomini et al., 2020). The Marula (Sclerocarya birrea), native to Africa, has edible fruits and seeds rich in oil and protein. These seeds are used in animal feed and more recently for biodiesel. Typically reaching 9-12 meters tall (up to 18 meters), the tree has a rounded shape, spreading crown, and a short bole up to 4 meters tall and 1.2 meters wide. Its grey, fissured bark and deep taproot (about 30 meters) help it thrive in dry, semi-arid environments (POWO, 2021). Bhardwaj et al. (2014) examined a CI engine fueled with B10, B15, and B20 blends from used cottonseed oil, finding B10 had the best performance with higher brake power and efficiency, and lower fuel consumption and exhaust temperature compared to B15 and B20. Gautam et al. (2022) compared engine metrics using diesel blends with Jatropha oil and biodiesel, noting similar performance despite Jatropha's higher flash point. Senthilkumar et al. (2012) tested cottonseed oil-diesel blends from B5 to B100, observing higher fuel consumption at B40 and B100, while B20 showed better efficiency. Aransiola et al. (2012) found Jatropha biodiesel reduced CO emissions, with NOx ranging from 5.27% to 10.74% in B60-B100 blends, and neem biodiesel blends from 1.39% to 11.9%. Gaurav et al. (2013) and Verma et al. (2019) indicated 20% biodiesel blends can be used in CI engines without modifications. Increasing engine compression ratio generally decreases fuel consumption, CO, and HC emissions, while increasing efficiency, NOx, and power (Padmanabhan et al., 2017; Sakthivel et al., 2020; Prasad et al., 2020). Experiments on marula biodiesel blends by Enweremadu & Rutto (2016) and Ejilah et al. (2017) showed these blends improve CO and HC emissions despite slightly higher NOx. While studies exist on Jatropha, neem, and cottonseed oil, comprehensive research on performance characteristics and emissions behavior of marula biodiesel blends under different loading conditions is limited. Further study is needed to find optimal blending ratios for improved engine efficiency and reduced emissions. This research aims to produce biodiesel from marula seed oil and evaluate its performance and emissions in a CI engine under various load conditions.

MATERIALS AND METHODS

Sample Collection and Preparation

Fresh marula fruits were collected from Waziri Umaru Federal Polytechnic in Birnin Kebbi and nearby areas in Nigeria. The fruits were manually crushed in a mortar to remove the outer shell; the wet, exposed fruits were then sun-dried, and the shells were mechanically broken using a hammer mill to reveal the kernels. Figures (1a-d) show the ripe marula fruits, wet exposed marula fruits, dry exposed marula fruits, and marula kernels, respectively. A solvent extraction method was employed to determine the actual oil yield levels of the kernels, using a Soxhlet apparatus under standard conditions as recommended by Luque-Rodriguez.

Figure 1: (a) Collected Ripe Marula Fruits, (b) Marula Fruit Exposed, (c) Dry Exposed Marula Fruit, and (d) Marula Fruit kernel

Transesterification

The experiment was conducted in a laboratory-scale batch apparatus. Transesterification occurred in a 1000 ml reaction flask with reflux condenser and digital magnetic stirrer. 95 g of marula oil was weighed, preheated to 100°C to remove water, then cooled to 60°C. A methanol solution (99.5% purity) and 1.33 g of potassium hydroxide (1.4 wt%) were added as catalyst at a 6:1 potassium methoxide-to-oil volume ratio. The mixture was stirred for 30 minutes at 305.5 rpm and 60°C.

A separating funnel was employed and allowed to settle for approximately 12 hours to ensure complete separation of glycerol from marula oil methyl ester (MOME). Upon settling, the biodiesel formed the upper layer, while glycerin and other impurities remained as the lower layer. The lower layer was carefully removed, and the MOME biodiesel was collected. Approximately 50 ml of distilled water at 50°C was added to the MOME product, gently swirled, and left for 2 hours to facilitate washing and removal of excess methanol and soap formed during the process. This washing procedure was repeated until the final MOME product was pure, with a pH value between 6 and 7. A small quantity of anhydrous magnesium sulphate was added and stirred for 5 minutes. Subsequently, the biodiesel was filtered through cotton wool to separate it from the hydrated magnesium sulphate and was then heated at 100°C in an oven to eliminate residual alcohol and water. The yield of the biodiesel was calculated using

$$\% \text{ oil yield} = \frac{weight\ of\ oil}{weight\ of\ sample} \times 100 \quad (1)$$

Characterization of the Marula Oil and Biodiesel Produced

The characterization of the Marula Oil and Biodiesel produced were done according to ASTM D6751 and EN 14214 standards.

Test Bed Operation

The engine used for the performance test is comprehensively described in Table 1. It is a four-stroke compression ignition engine with a single cylinder, equipped with a hydraulic dynamometer to measure torque at a steady speed of 1800 rpm (Plate 1). Experiments were conducted using diesel fuel and marula biodiesel blends (B10-B100) under loading conditions ranging from 500 g to 3000 g. For each fuel sample, the engine's consumption of 8 milliliters of fuel, torque, exhaust temperature, and barometric pressure were recorded. To establish a baseline for comparison, performance tests on pure diesel were also performed. The engine performance metrics, including Brake-specific fuel consumption, Brake Power, and Brake Thermal Efficiency, were documented while varying blend and load percentages. Gaseous emissions such as Nitrogen Oxides (NOx), unburned hydrocarbons (UHC), carbon monoxide (CO), and carbon dioxide (CO2) were measured using an SV-5Q automobile exhaust gas analyzer to evaluate operational performance. The findings from the performance analysis were compiled, and relevant parameters were illustrated graphically.

Table 1: Technical Specifications of Engine Test Rig

S/N	Parameters	Engine specification
1	Engine configuration	Single-cylinder, water-cooled CI engine
2	Bore x stroke	65 mm x 70 mm
3	Brake Power	2.43 kW
4	Speed	1800 rpm
5	Compression ratio	20.5:1
6	Starting method	Manual cranking
7	Net weight	45 kg
8	Manufacturer	TQ Educational Training Ltd
9	Model	TD 110-115

Plate1: Engine Test Rig

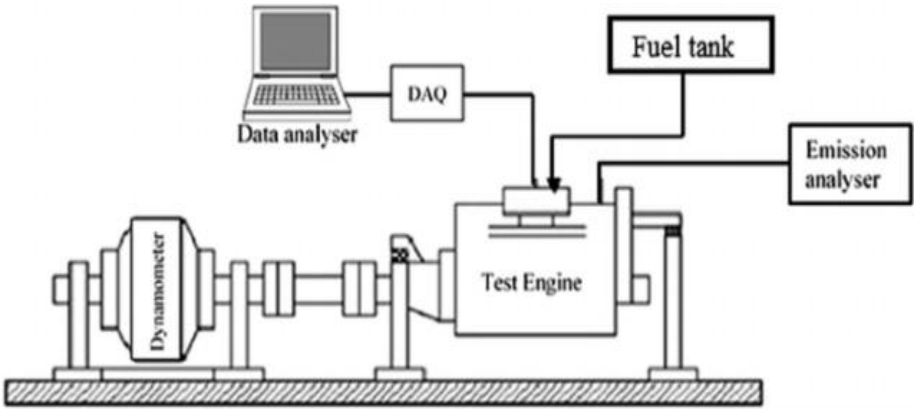

Figure 2: Schematic Diagram of Engine Test Rig, TD 110-TD 115 Test Bed Manual (2000)

Engine Performance Parameters

Torque

The torque was analysed by measuring the effects of a force acting at a distance from the shaft centre, and it can be characterised as a turning or twisting effort.

$$T = FL \quad (2)$$

Brake- Specific Fuel Consumption

Engine brake power output and the fuel's mass flow rate are used to calculate brake -specific fuel consumption. It is a crucial metric for evaluating engine performance and fuel economy.

$$\text{Brake Specific fuel consumption (SFC)} = \frac{volume\ flow\ rate\ of\ fuel}{brake\ power} = \frac{m_f\,(kg/h)}{p_b\,(KW)} \quad (3)$$

$$m_f = \frac{volume\,(l)}{time\,(hr)} \times \text{relative density of the fuels}\ (kg/l) \quad (4)$$

Brake Specific Energy Consumption

The quantity of gasoline produced by the engine to generate one unit of work.

$$(\text{BSEC}) = \frac{m_f\,(kg/h)}{p_b\,(KW)} \times C.V \quad (5)$$

Brake Thermal Efficiency

The ratio of the braking power production to the chemical energy input in the form of fuel supply.

$$\text{BTE} = \frac{BP}{m_f \times CV} \quad (6)$$

RESULTS AND DISCUSSION

Percentage Oil Yield

The oil content of the marula kernel was 58.7%. This value is higher in comparison with other vegetable oils, such as candlenut seed at 32.3%, Calodendrum capense seed at 35.4% (Ndaya, 2013), desert date linseeds at 33.33%, soybeans at 18.35% (Gunstone, 2004), Jatropha at 52.20%, and neem at 39.7% (Aransiola et al., 2012; Martín et al., 2010). However, it is lower than the 78% observed in avocado seed (Dagde, 2019). The oil content is influenced by the seed source and the soil texture, which also affects lipid development. Compared to other feedstocks, marula seed exhibits a high oil content. In comparison with other feedstocks, Marula seed has a high oil content.

Characterization of the Marula Oil and Biodiesel Produced

The results obtained are presented in Table 2. The physicochemical properties of marula biodiesel were assessed and compared with those of fossil fuels to determine whether marula biodiesel could be used as a replacement fuel in a compression-ignition engine. The marula fuel properties were analyzed and compared with the requirements of internationally recognized biodiesel standards, such as ASTM D6751 and EN 14214. The density (880 kg/m3) and specific gravity (0.880) of marula biodiesel were higher than those of diesel (850 kg/m3 and 0.850, respectively). The higher density fuels influence the fuel injection process by delivering a slightly greater mass of fuel into the combustion chamber at the same injection volume, which also affects the spray characteristic and fuel-air mixing process inside the combustion chamber (Nalla et al., 2025).

In general, biodiesel fuel has a higher density and viscosity than fossil fuels due to its fatty acid methyl ester composition (Senthil & Vijay, 2023; Suardi et al., 2024 ; Mustapha et al., 2025)

The kinematic viscosity of marula biodiesel at 5.0 mm^2/s, exceeds that of diesel fuels, which is 4.0 mm^2/s; however, it remains within the permissible range specified by ASTM D6751. Compared with diesel fuel, the higher viscosity may result in slightly larger fuel droplets during injection. Nonetheless, since these values fall within established regulatory limits, they are deemed suitable for engine operation. Diesel fuel has a higher calorific value of 44.70 MJ/kg than biodiesel's 42.89 MJ/kg. A typical characteristic of biodiesel is the reduced heating value, attributable to the presence of oxygen atoms in the fatty acid methyl ester (Thokchom, 2024; Mujtaba et al., 2020), which diminishes the fuel's energy density. Consequently, biodiesel generally exhibits heating values that are 8-12% lower than those of diesel, leading to a marginal increase in specific fuel consumption during operation and shows a slight increase in specific fuel consumption when operating (Alahmer et al., 2022; Mujtaba et al., 2020). Biodiesel has a higher Cetane number (55.1) than diesel (46.0), which improves engine performance by reducing ignition delay, improving combustion smoothness, and increasing combustion efficiency. Marula biodiesel had a higher flash point of 175 ℃ than diesel of 68℃**.** This confirms the safe handling, transportation, and storage. Due to its lower volatile hydrocarbon content, biodiesel typically has a higher flash point than diesel fuel (Suleiman et al., 2020; Costa et al., 2024). The pour point and cloud point of biodiesel ($3℃, and\ 8℃$) was higher than that of diesel fuel (-$16℃, and - 12℃$) respectively. The higher pour point indicates that biodiesel loses its flowability at relatively higher temperature. The higher cloud points are commonly observed in biodiesel fuel due to saturated fatty acid methyl ester, which begin to crystallize as the temperature decreases (Bouaid et al., 2024; Mustapha et al., 2025)

T**able 2: Fuel Properties of Extracted Marula Oil and Transesterified Marula Oil**

Fuel Property	Diesel	Marula Oil	B100	ASTM D6751	EN 14214
Moisture Content % (w/w)	0.015	4.4	0.04	<0.05	<0.05
Acid Value (mg KOH/g)	-	3.42	0.44	≤ 0.5	≤ 0.5
Iodine Value (mgI/g)	-	61.77	-	115 max	120 max
Saponification Value (mgKOH/g)	-	187.72	-	180 - 200	-
Specific gravity	0.850	0.943	0.880	0.910-0.940	-
Flash point ℃	68	240	175	≥ 130	≥ 120
Pour point ℃	-16	5	3	-	-
Cloud point ℃	-12	10	8	-	-
Calorific Value (MJ/kg)	44.70	38.40	42.89	42	-
Viscosity (mm^2/s)	4.0	41.0	5.0	1.9 -6.0	3.5 – 5.0
Cetane number	47.0	51.0	55.1	≥47	. ≥51
Density (kg/m^3)	850	943	880	-	860- 900

Engine Performance Analysis

Brake Torque

Brake torque represents the effective rotational force developed at the crankshaft and reflects the engine's load-carrying capability. Brake torque change with engine load (500-3000 g) at a steady speed of 1800 rpm was presented in Figure 3. The torque generated increased monotonically with load for all fuel samples, reaching a maximum at 2500 g. The peak torque values recorded were 13.52 Nm and 13.46 Nm for B10 and neat diesel (D100), respectively. A gradual reduction in torque was observed as the biodiesel fraction increased beyond B10. The increase in torque from B10 to B30 can be attributed to the synergistic effects of marula biodiesel's higher cetane and the higher calorific value of diesel in the blends. The enhancement in torque shows more complete combustion and improved combustion efficiency (Karthikeyan & Prathima, 2016). Slight reduction in brake torque at higher biodiesel proportions is attributed to the lower heating value of biodiesel (Sathish & Singaravelu, 2020).

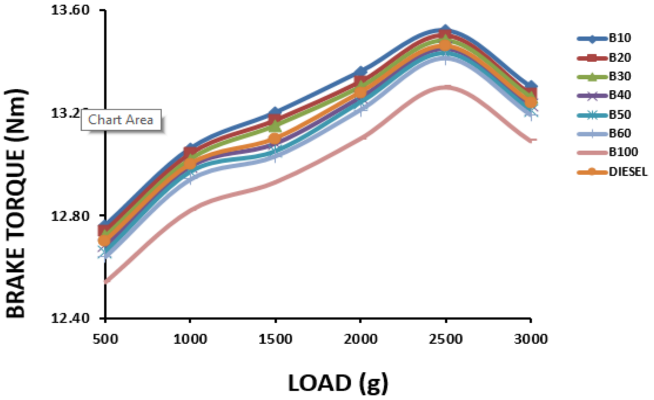

Figure 3: Brake Torque Variation with Engine Load

Brake Power

Brake power can be defined as the net shaft power delivered by the engine. Higher brake power shows superior engine performance (Attia, et al., 2020). Brake power for different fuel blends was illustrated in Figure 4. The brake power increased progressively with load for all tested fuels, reaching a maximum at 2500 g before declining slightly at higher loads. The usual diesel was lower than B10, B20, and B30.

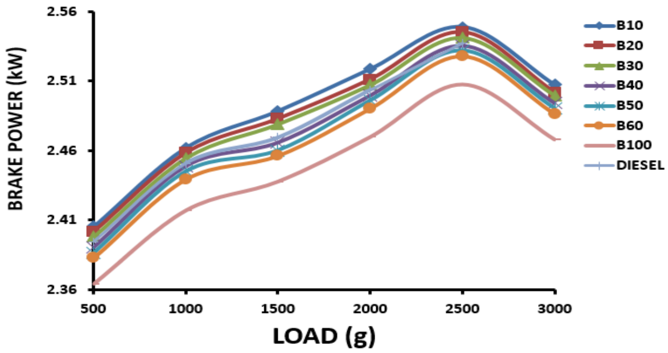

Figure 4: Variation of Brake Power with Engine Load

Brake- Specific Fuel Consumption

Brake-Specific Fuel Consumption (BSFC) is the mass flow rate of fuel per unit Brake Power Output and provides a direct measure of fuel economy. Fig 5 shows how BSFC changes with diesel engine load and various biodiesel blends. BSFC decreases as load increases, reaching a minimum at 2500 g, then rises slightly. This indicates that the engine operates at optimal conditions (Maawa et al., 2015). BSFC of B30 was slightly lower than that of diesel. This could be improved by using biodiesel with a higher cetane number and adjusting the combustion timing (Gangil et al., 2016). Biodiesel with a lower calorific value and improved combustion efficiency may overcome this limitation at moderate blending ratios.

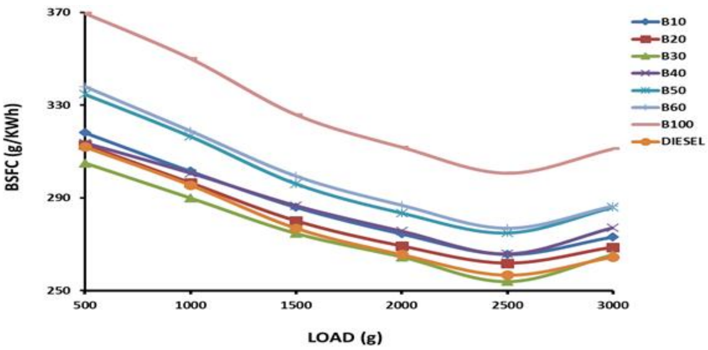

Figure 5: BSFC Variation with Engine Load

Brake -Specific Energy Consumption (BSEC)

Brake -Specific Energy Consumption (BSEC) is the energy input required to produce a unit of brake power output (Duc et al., 2019). As shown in Figure 6, BSEC decreased consistently as load increased for all fuel blends. However, B20 and B30 exhibited lower BSEC compared with diesel fuel. The reduction in BSEC can be attributed to the fact that the percentage increase in fuel consumption was lower than the corresponding increase in Brake Power. Initial reduction can be explained as improved and more complete combustion at moderate loads (Selvakumar et al., 2015).

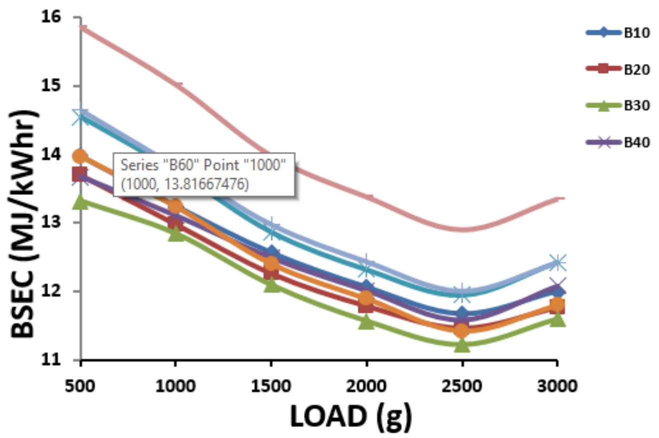

Figure 6: BSEC Variation with Engine Load

Brake Thermal Efficiency (BTE)

Brake Thermal Efficiency is the ratio of brake power output to the chemical energy input supplied by the fuel (Tesfa et al., 2011). It serves as a direct indicator of the effectiveness of converting thermodynamic input to mechanical work. Figure 7 presents the variation in brake thermal efficiency with engine load for diesel and MOME-diesel. Brake Thermal Efficiency increases with load for all fuel samples, reaching a maximum at 2500 g. The increase in BTE at higher loads can be attributed to reduced relative heat losses and improved cylinder pressure development. However, beyond 2500 g load, a slight decrease in BTE was observed, likely due to reduced time available for complete combustion at higher loads. Ingle & Nandedkar (2013) state that an engine running on biodiesel usually has a higher thermal efficiency than one running on diesel because of the biodiesel's higher lubrication and oxygen content. B30 improved brake thermal efficiency by approximately 3-5% compared with diesel.

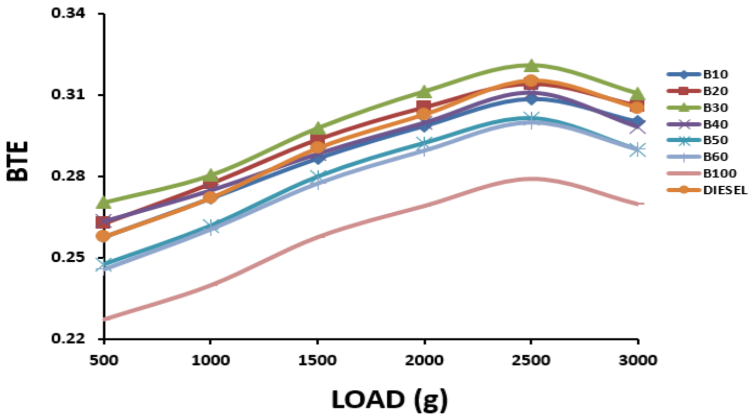

Figure 7: Variation of BTE with Engine Load

Engine Emission Analysis

Carbon Monoxide Emission of Diesel Fuel and MOME-Diesel Blends

Incomplete combustion of fuel, in the combustion chamber of a compression ignition engine, produces carbon monoxide (CO). An intermediate combustion product that is poisonous and undesirable as a flue gas. It has been observed that as the load increases, CO emissions increase. Ismail et al. (2014) looked at the CO emissions of castor oil and discovered that they were 60 parts per million, compared to 79 parts per million for regular diesel. Krahl et al. (2003) found that biodiesel made from the rapeseed oil reduced CO emissions by almost 50% when compared to low-diesel fuel.

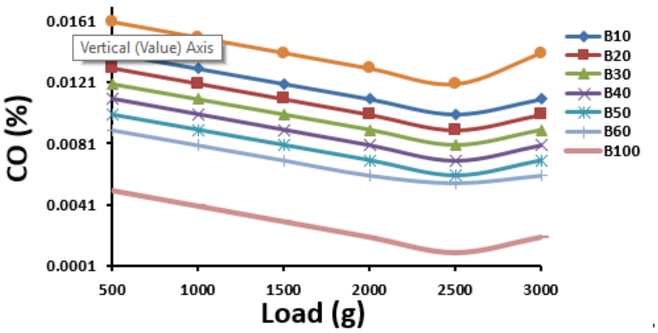

Figure 8: CO Emission for Diesel Fuel and MOME-Diesel Fuel Blends Under Various Load

CO_2 Emission of Diesel Fuel and MOME-diesel Blends

A lower percentage of biodiesel blends results in reduced CO_2 emissions. This may be attributed to biodiesel having a lower carbon-to-hydrogen ratio compared to diesel. Larger blends emit CO_2 levels that are nearly comparable to those of diesel fuel (Dhamodaran *et al.,* 2017). By utilizing a life cycle assessment of CO_2, the impact of biodiesel on global greenhouse gas emissions was evaluated, revealing that, in comparison to petroleum diesel, biodiesel reduces CO_2 emissions by approximately 50-80% (Abed *et al.*, 2019). The CO_2 produced during combustion is effectively separated from the environment through the cultivation of crops that produce vegetable oil; therefore, biodiesel is considered to be carbon neutral (Sahoo *et al.*, 2007).

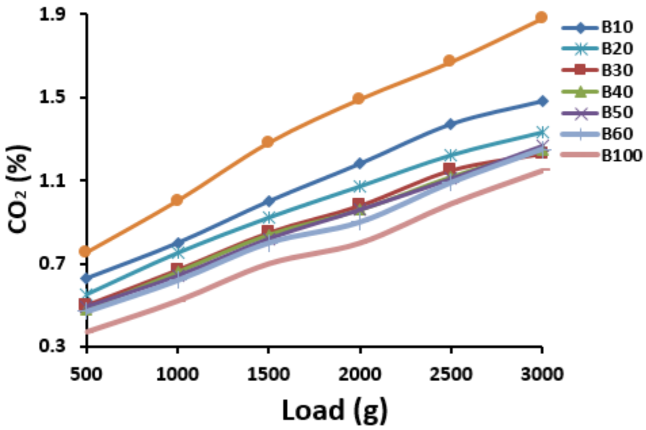

Figure 9: CO_2 Emission for Diesel and MOME-Diesel Blends under Various Loading Conditions

HC Emission for Diesel Fuel and MOME-diesel Blends

The amount of unburned HC in the exhaust system, as a result of incomplete fuel combustion, is indicated by the hydrocarbon percentage. Because it minimizes power loss, fuel with less HC is preferable (Attia *et al.*, 2020). The decrease in HC emissions for the biodiesel blends can be attributed to the presence of oxygenated compounds in the biodiesel, which promote more complete combustion. The HC emissions of engines running on waste cooking oil synthetic diesel (WCOSD) were studied (Nguyen *et al*., 2020). They discovered that, on average, the HC emissions of the WCOSD were 26.3% lower than for engines running on conventional diesel (CD).

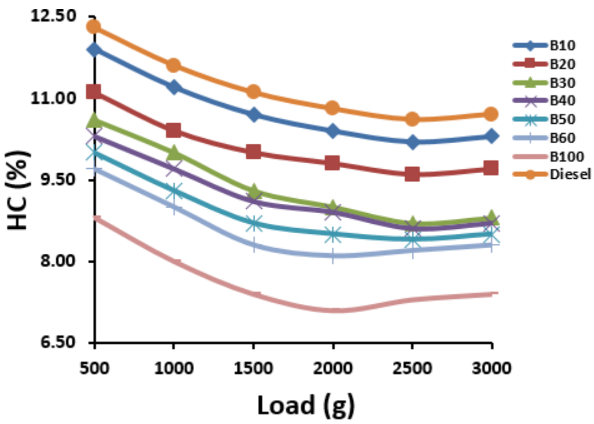

Figure 10: HC Emission for Diesel and MOME-Diesel Blends under Various Loading Conditions

Nitrogen Oxides (NOx)

Nitrogen Oxide (NOx) is produced through chain reactions involving nitrogen and oxygen in the presence of air. The variation in NOx emissions for MOME blends and diesel fuel is illustrated in Figure 11. The trends in NOx emissions for all fuel samples exhibited an increase with rising load and increasing MOME percentage in the diesel fuel. For the blends, an increase in emissions was observed at all load levels compared to diesel fuel. At higher loads, a greater amount of fuel is combusted, and the elevated temperature of the exhaust gases leads to increased nitric oxide production. The oxygen content in biodiesel facilitates complete combustion of the fuel, resulting in reduced emissions of CO and HC, and a marginal increase in NOx emissions of biodiesel (Gangil et al., 2016).

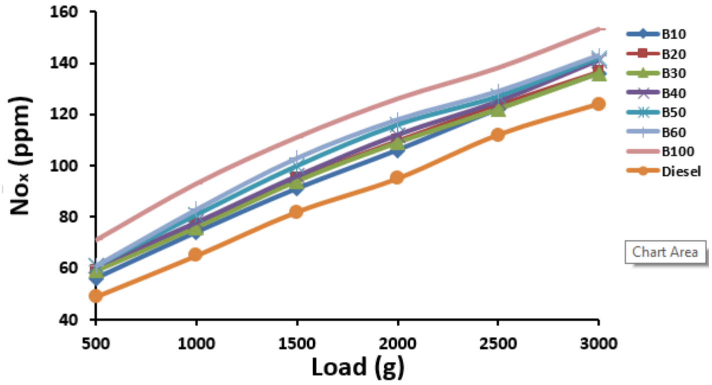

Figure 11: NOx Emission for Diesel and MOME-Diesel Blends under Various Loading Conditions

CONCLUSION

The following observations were drawn after completing this work.

i. Marula kernel exhibited a high oil yield of 58.7%, indicating strong potential as a biodiesel feedstock.

ii. The biodiesel produced satisfied the ASTM D6751 and EN 14214 fuel property standards.

iii. Engine torque increases with load for all fuel samples, reaching a peak value of 13.52 Nm at 2500 g for B10. The torque produced for B10, B20, and B30 were also higher than conventional diesel; the torque decreased progressively with increasing biodiesel content beyond optimal blending levels. This reduction at higher blend ratios may be due to biodiesel's lower caloric value and higher viscosity.

iv. Brake power increased with load up to 2500 g and decreased thereafter. The brake power of B10, B20 and B30 was higher than that of diesel fuel across the tested load range, with B10 showing the best overall performance.

v. For every fuel sample, the Brake Specific Fuel Consumption (BSFC) dropped as the load increased, reaching a minimum value of 2500 g before steadily rising. The B30 was less than that of the diesel product. The B30 blend produced the best BSFC among all tested samples.

vi. Up to a load level of roughly 2500 g, there was a decrease in BSEC with increasing load; after that, there was a modest increase. However, as the blend ratio increased, BSEC declined until reaching B30, after which it began to climb. The highest BSEC value was observed with B30.

vii. Brake thermal efficiency (BTE) improved with load, with B20 and B30 outperforming conventional diesel. The highest BTE was observed for B30.

viii. Biodiesel blends significantly reduce CO and HC emissions, NOx increased slightly with higher biodiesel ratios.

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