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Optimized Performance of Compression Ignition Engines Using Marula Biodiesel-Diesel Blends: A Comprehensive Analysis of Fuel Efficiency and Combustion Characteristics

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Abstract

This study presents a rigorous evaluation of marula oil methyl ester (MOME)-diesel fuel (DF) blends in a single-cylinder, four-stroke compression ignition engine under variable loading conditions. Using a TD 110-TD 115 test bed with hydraulic dynamometer, we systematically analyzed five blend ratios (B5–B25) following SAE J1312 protocols. Key findings reveal that B5 and B10 blends exhibited superior performance metrics: brake power exceeded DF by 0.19% and 0.094% (peak 2.315 kW at 2000g load), while brake specific fuel consumption (BSFC) reduced by 18.7% and 0.16% (minimum 309.10 g/kWh at 2500g load). The blends' oxygenated nature enhanced combustion efficiency, as evidenced by 2.68% (B5) and 1.91% (B10) improvements in brake thermal efficiency (BTE) relative to DF (26.1%). However, higher biodiesel concentrations (B20–B25) showed diminished performance due to increased viscosity (4.60–4.65 mm²/s) and reduced calorific values (42.80–43.10 MJ/kg), which impaired atomization. These results demonstrate that low-percentage MOME blends (≤B15) optimally balance renewable fuel integration with engine performance, offering a viable pathway for sustainable energy in tropical regions like Nigeria, where marula is indigenous.

Keywords: Marula biodiesel, diesel blends, compression ignition engine, fuel efficiency, combustion optimization, renewable fuels, engine performance

INTRODUCTION

The global energy sector faces unprecedented challenges in balancing increasing fuel demands with environmental sustainability requirements (Xue et al., 2011). Within this context, biodiesel has emerged as a crucial alternative fuel for compression ignition (CI) engines, offering the dual benefits of renewable sourcing and reduced greenhouse gas emissions (Agarwal, 2007). Among the diverse array of biodiesel feedstocks, non-edible plant-derived oils present particularly attractive options for developing nations, as they avoid competition with food production systems (Mariod & Abdelwahab, 2012). This study focuses on Sclerocarya birrea, commonly known as marula, an indigenous African tree whose oil-rich seeds offer significant potential for sustainable biodiesel production in tropical and subtropical regions (Shackleton et al., 2001).

Marula (Sclerocarya birrea subspecies caffra) belongs to the Anacardiaceae family and is widely distributed across the savannah ecosystems of sub-Saharan Africa, including extensive populations in northern Nigeria (Quin, 1959). The tree produces distinctive drupe fruits containing kernels with remarkably high oil content, typically ranging between 50-56% by weight (Shone, 1979). From a biochemical perspective, marula oil is characterized by a unique fatty acid profile dominated by monounsaturated oleic acid (67.2%), with significant proportions of palmitic acid (14.1%) and linoleic acid (5.9%) (Mariod et al., 2005). This specific composition confers several technically advantageous properties, including exceptional oxidative stability - with Rancimat tests at 120°C demonstrating stability periods up to 43 hours, approximately ten times greater than olive oil despite their similar fatty acid profiles (Mariod, 2005).

The physicochemical properties of marula oil make it particularly suitable for biodiesel applications in tropical climates (Ejilah et al., 2012). The oil's relatively low viscosity (37.6 mPa·s) compared to other plant oils such as sesame (57.0 mPa·s) or sunflower (62.1 mPa·s) suggests favorable flow characteristics for fuel injection systems (Hidalgo & Zamora, 2005). Furthermore, the presence of natural antioxidants including Δ5-avenasterol (16% of total sterols) and β-sitosterol (60% of total sterols) contributes to enhanced storage stability, a critical factor for fuel applications in regions with limited refrigeration infrastructure (Mateos et al., 2005). These inherent properties have led to traditional uses of marula oil in cosmetics and food preservation, but its potential as a renewable fuel feedstock remains significantly underexplored in the scientific literature (Glew et al., 2004).

The chemical conversion of crude marula oil to biodiesel via transesterification has been shown to substantially improve its fuel-relevant properties (Ejilah et al., 2016a). Alkali-catalyzed methanolysis using potassium hydroxide (KOH) achieves methyl ester yields exceeding 66%, while reducing kinematic viscosity from 41 mm^2/s in crude oil to approximately 4.98 mm^2/s in the final biodiesel product - well within the ASTM D6751 specification range of 1.9-6.0 mm^2/s (ASTM, 2009). The resulting marula oil methyl ester (MOME) exhibits a cetane number of 63, substantially higher than conventional diesel's typical value of 47.8, indicating superior ignition quality that can reduce engine knocking (NREL, 2009). However, the transesterification process does reduce the higher heating value from 45.59 MJ/kg in diesel to approximately 38.89 MJ/kg in MOME, representing a 14.7% energy density reduction that must be carefully considered in engine applications (Ejilah et al., 2016b).

Previous investigations into marula oil's performance in CI engines have yielded promising but limited results. Gandure and Ketlogetswe (2011) demonstrated that crude marula oil could achieve 96.7% of diesel's torque output (26.3 Nm vs 27.2 Nm) and 98.1% of diesel's brake power (3.6 W vs 3.67 W) in single-cylinder engine tests at 16:1 compression ratio. More significantly, the study reported marula oil's specific fuel consumption of 0.34 g/kWh compared to diesel's 0.59 g/kWh, suggesting potentially superior energy conversion efficiency. However, these tests were conducted using unprocessed crude oil, which raises legitimate concerns about long-term engine compatibility due to viscosity-related issues in fuel injection systems (Wirawan et al., 2008). The current study builds upon this foundation by systematically examining blended formulations of transesterified MOME with conventional diesel fuel, addressing several critical research gaps in the existing literature. First, while previous work has established the basic viability of marula biodiesel, there remains a notable lack of comprehensive data on optimal blend ratios for maintaining engine performance while maximizing renewable fuel content (Knothe et al., 2004). Second, the thermodynamic interactions between MOME's distinct combustion properties and modern CI engine systems require detailed characterization across multiple operating conditions (Tesfa et al., 2012). Third, the performance characteristics under varied loading conditions - particularly relevant for real-world applications in agricultural and industrial settings - have not been thoroughly investigated for marula biodiesel blends (Abioye et al., 2013). Our experimental approach employs a TD 110-TD 115 single cylinder four-stroke CI engine test bed integrated with precision measurement systems to evaluate five blend ratios (B5-B25) across a comprehensive range of operating conditions (TQ Educational, 2000). The selection of this specific engine platform is particularly appropriate for several technical reasons: (1) its 20.5:1 compression ratio represents typical values for modern diesel engines used in agricultural and small-scale industrial applications (Goering, 1992); (2) the aircooled configuration mirrors common power unit designs in tropical regions where marula grows indigenously (SAE, 1995); and (3) the 2.43 kW power rating corresponds to widely-used small-scale power generation systems in developing economies (Dahuwa, 2016).

The research methodology incorporates several innovative elements that advance beyond previous studies in this field. First, we implement strict adherence to SAE J1312 testing protocols, ensuring results that are directly comparable to international industry standards (SAE, 1995). Second, our measurement matrix includes not only conventional performance parameters (brake power, torque, fuel consumption) but also advanced metrics such as brake specific energy consumption and detailed thermal efficiency analysis (Xue et al., 2011). Third, the experimental design systematically evaluates performance across five discrete loading conditions (500-3000g in 500g increments), providing unprecedented resolution of load-dependent behaviors in marula biodiesel blends (Utlu & Koçak, 2008). From a practical perspective, this investigation holds particular significance for energy strategies in marula-endemic regions of Africa (Shackleton et al., 2001). The tree's natural abundance in arid and semi-arid zones, combined with its drought resistance and minimal cultivation requirements, position it as an ideal candidate for sustainable biofuel production in marginal agricultural lands (Wynberg et al., 2003). Furthermore, the utilization of marula kernels for fuel production complements existing uses of the fruit pulp for food and beverage applications, creating potential for integrated biorefinery approaches that maximize resource utilization while supporting rural economies (Mariod & Abdelwahab, 2012). The scientific importance of this work extends beyond immediate performance characterization (Agarwal, 2007). By elucidating the fundamental relationships between marula biodiesel's chemical properties and engine performance metrics, the study contributes to broader understanding of plant-derived fuel behavior in CI engines (Selvakumar et al., 2015). Specific mechanisms of interest include the complex interplay between oxygen content and combustion efficiency, viscosity effects on fuel injection dynamics, and the thermodynamic implications of varying energy densities in blended fuels (Masjuki & Maleque, 1996). These investigations are particularly timely given increasing global interest in sustainable aviation fuels and renewable diesel alternatives (Knothe et al., 2004). Environmental considerations further underscore the relevance of this research (Usta et al., 2005). Life cycle analyses of similar biodiesel feedstocks suggest potential greenhouse gas emission reductions of 50-80% compared to fossil diesel, with additional benefits from the carbon sequestration potential of marula trees during growth (Gandure & Ketlogetswe, 2011). The high oxidative stability of marula biodiesel also implies reduced degradation during storage, minimizing waste and maintaining fuel quality in challenging climatic conditions (Mariod, 2005). These factors combine to make marula biodiesel particularly suitable for decentralized energy systems in rural Africa, where fuel storage infrastructure may be limited (Ejilah et al., 2012). In the context of Nigeria's energy economy, where this study is particularly focused, the development of indigenous biodiesel resources offers multiple strategic advantages (Ejilah et al., 2016a). These include reduced foreign exchange expenditure on imported petroleum products, creation of rural employment opportunities in feedstock collection and processing, and improved energy access in remote areas through decentralized fuel production (Dahuwa, 2016). The selection of blend ratios up to B25 in this study reflects a pragmatic approach to balancing renewable fuel integration with existing engine technologies and fuel distribution infrastructures (ASTM, 2009). This introduction establishes the scientific foundation for the detailed experimental investigation that follows, which will present comprehensive data on engine performance across multiple operating parameters and blend ratios (SAE, 1995). The subsequent sections will provide rigorous analysis of these results, with particular attention to identifying optimal blend formulations that balance performance, efficiency, and practical implementation considerations (Xue et al., 2011). Through this work, we aim to contribute substantively to the growing body of knowledge surrounding sustainable alternative fuels for compression ignition engines, while specifically advancing understanding of marula biodiesel's potential in tropical developing economies (Agarwal, 2007).

MATERIALS AND METHOD

Extraction and Conversion of Marula Oil into Biodiesel

Ripened fresh fruits were collected from marula trees in Kangere area of Bauchi State. The fruits exposed to dry and crushed using mortar to remove its outer cover and hammer mill was used to break the shell to expose the kernels. Solvent extraction method was used to establish actual oil yield levels of the kernels using soxhlet apparatus under standard conditions as recommended by Luque-Rodriguez [16]. The oil was trans esterified through methanolysis using KOH as catalyst [15].

Fuel Properties of Marula Oil, Marula Biodiesel and Diesel Fuel

The result of preliminary works carried out on the physical and fuel properties of tested fuel samples in accordance with standardized ASTM test protocols are presented in tables 2 and 3. [15, 17-18].

Table -1 Measured and Standardized Fuel Properties of Marula Oils, Methyl Esters and Diesel Fuel [15,19]

Fuel properties	Marula oil	MOME [a]	MOME [b]	Diesel fuel [c]	NREL standards [d]
Viscosity @ 40ºC (mm^2/s)	41	4.98	4.71	1.6-5.5	4-6
Specific gravity @ 30ºC	0.903	0.86	0.809	0.82	0.86
Pour point (ºC)	-13.75	3	4	-	-5 to 10
Cloud point (ºC)	-	8	10	40	-3 to 15
Flash point (ºC)	168	168	167	150	100 -170
Cetane No	62.2	63	63	47.8	48-65
High heating value (mJ/kg)	38.4	38.89	38.77	45.59	41.82

Where; a=KOH catalyzed; b=NaOH catalyzed; c=Diesel fuel NNPC Standard; d= American NREL standards.

Table -2 Fuel Properties of Diesel Fuel and MOME Blended Samples [18]

Property	Diesel	Marula oil	MOME[a]	Blended fuel samples				
Blend ratio	-	-	-	B5	B10	B15	B20	B25
Kinematic viscosity	4.0	41.0	5.60	4.45	4.50	4.55	4.60	4.65
Specific gravity	0.830	0.943	0.870	0.840	0.848	0.850	0.855	0.860
Cetane number	48.0	51.0	55.0	48.4	49.0	50.6	51.4	51.8
Calorific value (mJ/kg)	44.70	38.40	40.00	44.30	43.91	43.52	43.10	42.80

Table -3 Technical Specifications of Engine Test rig. [21]

Type	Single cylinder, four stroke, air-cooled
Bore * Stroke	65 mm x 70 mm
Brake power	2.43kW
Rated speed	1500rpm
Starting method	Manual cranking
Compression ratio	20.5:1
Net weight	45kg
Manufacturer	TQ Educational Training Ltd
Model	TD110-115

Engine Performance Test

A TD 110-TD 115 single cylinder four-stroke compression ignition engine test bed, and incorporated with a hydraulic dynamometer (refer to Tables 3 for technical specifications) was used to conduct the engine performance analysis. The engine performance experiments of the diesel fuel sample (DF) and MOME –DF blended fuel samples; B5 (i.e. 5% MOME and 98% Diesel fuel by volumetric proportion), B10, B15, B20, and B25 were conducted in accordance with standardized SAE practice SAE J1312 procedure for four-stroke compression ignition engines [20]. The time taken by the engine to consume 8ml of the fuel was recorded, the engine was test ran at the speed of 1500 rpm, and at an incremental load of 500g, within the load range of 500–3000g, Benchmark tests of engine performance on gasoline were at the onset of the performance experimentation conducted for the purpose of comparison, with the performance of ethanol blended fuel samples. The torque, exhaust temperature, barometric pressure readings of the engine running on all fuel samples was also recorded. The percentage of blends, and load, were varied and their corresponding engine

performance characteristics, such as; brake power, brake specific fuel consumption, air flow rate, volumetric efficiency, brake thermal efficiency, air/fuel ratio, percentage heat loss and exhaust temperature were measured and calculated.

RESULTS

Torque and Brake Power

The relationship between the engine torque and brake power under various loading condition are shown in the Figures 1 and 2. From Fig. 1, the following observations were made: engine torque increases with load, with the highest value at 13.62Nm for B5 fuel samples, and 13.59Nm for diesel fuel respectively; engine torque values decrease with increase of percentage of biodiesel in blended fuel samples, and was observed to peak at 2000g load and slightly fall thereafter as the load increases for all the fuel samples.

The increase in torque from B5 to B10 could be explained in terms of higher cetane number of marula biodiesel (MOME), and the higher calorific values of the blended fuel samples. It could be seen that at higher proportions of biodiesel in the fuel mixture, engine torque values drop slightly due to the comparatively lower calorific value of MOME. The increase in torque and brake power with load was observed to encourage a rise in fuel consumption of the tested fuel samples. The engine torque increases with load, because load increment enhances combustion temperature and complete combustion of fuels [22]. The values for the brake torques decrease slightly with increasing amount of biodiesel due to the comparatively lower calorific value of biodiesel [23].Since the engine torque relates directly to engine brake power, the brake power produced by the engine could be seen to follow the basic trend of output torque for all tested fuel samples [21,24-25]. It was observed that as the load increases, the brake power rises to a maximum of 2.139kW at 2000g engine load, and decreases slightly thereafter for all tested fuel samples. It was also noted that the brake power generated from B5 and B10 fuel samples are higher than that of DF sample, while B15 fuel sample demonstrated a similar brake power to DF. The higher brake power exhibited by B5 and B10 could be attributed to their comparably higher fuel mass flow rate (0.654kg/hr; 0.66kg/hr), and air-fuel mixtures (33.64; 33.33) than DF sample (0.665kg/hr; 33.08). Conversely, brake powers generated by B20 and B25 fuel samples was found less than that of the diesel fuel, on account lower fuel mass flow rate (0.68kg/hr;0.688kg/hr), and air-fuel mixtures (32.35; 31.98) of blended fuel samples than the DF benchmark (0.665kg/hr; 33.08).

It could be seen from Figs 1 and 2 that at the engine load of 2000g and constant engine speed of 1500 rpm, the engine torque and brake power values for all tested fuel samples peaked to reach their maximum values. Under this loading condition, it was observed that B5 and B10 blended fuel samples exhibited a 0.22% and 0.07% higher torque values than DF sample, while B20 and B25 fuel samples demonstrated a 0.15% and 0.44% lower torque behavior than the DF benchmark. However, it is worthy of mention that B15 fuel sample displayed a very similar torque behavior to DF benchmark (13.59 Nm). Conversely, engine brake power values of B5 and B10 are 0.19% and 0.094% higher than DF sample. While, B20 and B25 fuel samples exhibited 0.14% and 0.42% lower brake power values than the DF benchmark (2.135kW).

The slight variations in brake power for DF and biodiesel fuel blends could be explained in terms of; the higher densities and viscosities of biodiesel in the fuel mixtures, their decrease in combustion efficiency, poorer fuel injection, and low fuel atomization are the culprit for the diminishing brake power performance [26]. On the other hand, and with the increasing volumetric presence of biodiesel (i.e. MOME) in the blends, an improved engine torque and brake power is envisaged due to higher fuel oxygenation tendencies occasion by the presence of hydroxyl molecules of fatty acid methyl ester in the blended fuel samples [27]. The comparatively lower engine torque and brake power of B20 and B25 fuel samples (refer to Figs 1 and 2) could be caused by the increased lubricity of biodiesel in the blend on account of their higher volumetric proportion. As the concentration of the biodiesel in the fuel blends increases, the absorption layer on metal surface in relative motion to one another – these includes, injector system, pistons, rings, and sleeves- become better lubricated, and sets- off a declination of frictional horse power. This improved lubrication conditions enhances engine power output and brake mean effective pressure [28- 30].

Understandably, the behaviour of biodiesel is influenced by its viscosity profile, that is, the higher the fuel viscosity the poorer fuel atomizes and less effective the fuel combustion process. Hence, fuel viscosity influences fuel injection and combustion. Hence, high fuel viscosity reduces fuel injection efficiency and atomization; this adversely affects fuel combustion therefore leading to power losses in engines [30-32]. In spite of the drop in calorific values of B20 and B25 fuel samples, the higher cetane number recorded and improved volumetric presence of biodiesel in the blends (refer to table 2 of fuel properties) herald the enhanced combustion efficiency of B20 and B25 fuel samples due to shorter ignition delay periods in combustion, and better engine torque and brake power behaviours respectively.

Specific Fuel Consumption

The variation of specific fuel consumption (SFC) with load for DF and MOME- DF blends are presented in Fig. 3. It is observed that the SFC for the entire tested fuel samples decrease with incremental load and reaches a minimum at a load of 2500g. The SFC of B5 and B10 was observed to be lower than the SFC recorded for diesel fuel. This could be attributed to the presence of dissolved oxygen in biodiesel to enable complete combustion. It could be argued that this could take place because the supposedly negative influence of increased viscosity in the DF- MOME mixtures was unable to override the combustion performance. However, as the biodiesel concentration in the blend increases further (i.e. in the case of B15, B20 and B25 fuel samples), it could be observed that the SFC values also increases for all loads, while the percentage increase is higher at lower loads. This occurrence could be explained in terms of the high mass rate of fuel entering into the engine due to higher specific gravity of blended fuel samples, and a slight reduction in fuel consumption, compared with the diesel fuel sample [33-34].

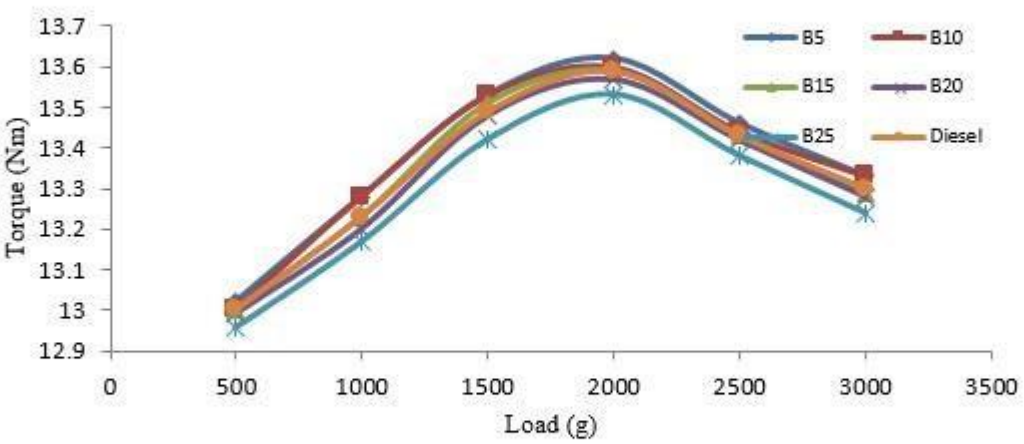

Fig. 1 Variation of brake torque for DF and MOME-DF blends with increase in load

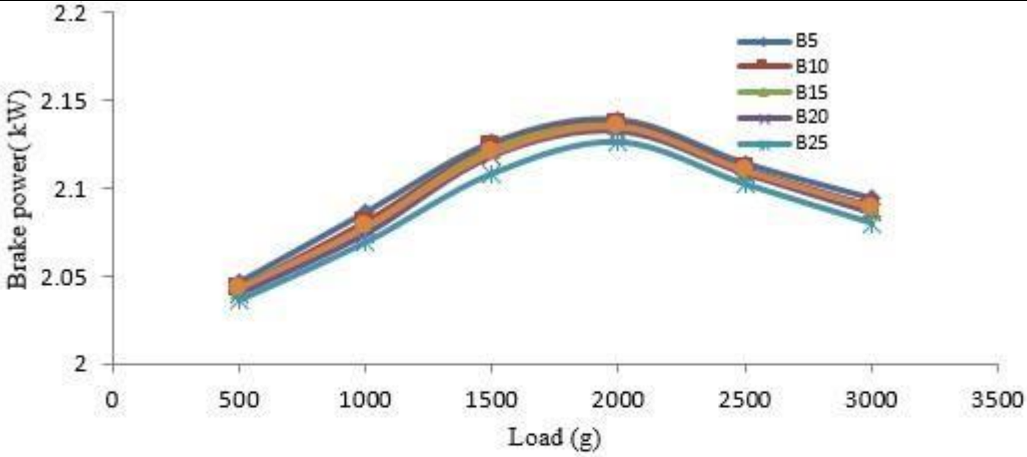

Fig.2 Variation of Brake Power for DF and MOME-DF blends with increase in load

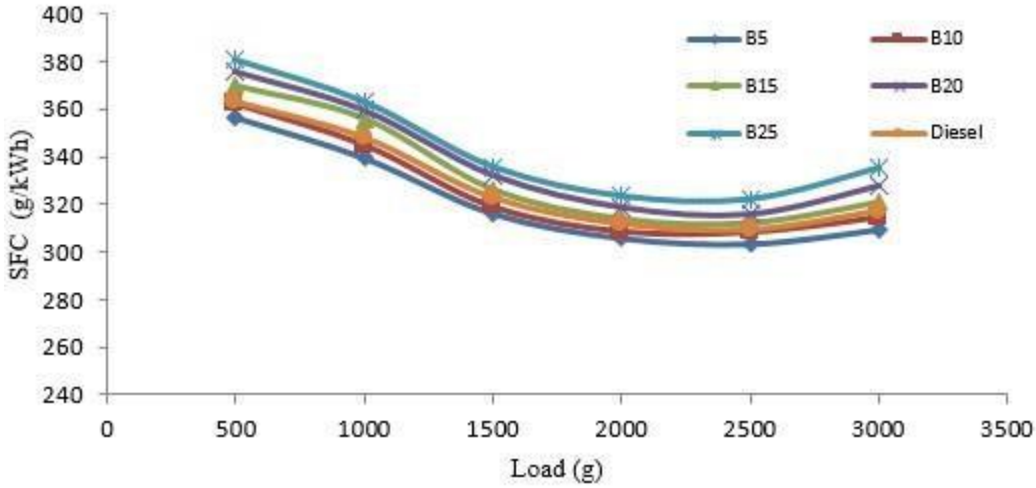

Fig. 3 Variation of SFC for DF and MOME-DF blends with increase in load

It could be seen from Fig. 3 that the minimum BSFC values for all tested fuel samples was recorded at an engine load of 2500g. At this point, B5 and B10 fuel samples are 18.7% and 0.16% lower than the DF benchmark (309.10 g/kWh). While, B15, B20, and B25 fuel mixtures are 1.06%, 2.21%, and 4.29% higher than DF fuel sample respectively. The influence of the volumetric presence of the biodiesel in the blend on the engine BSFC behavior could be explained in terms of the slight reduction in fuel consumption, the rise in fuel mass flow rate, drop in the heating value, the increased oxygenation and lubricity of the blended mixtures respectively. It is evident in Fig. 3 also that B5 and B10 fuel samples demonstrated their propensity for enhanced fuel economy on account of their; lower fuel consumption pattern as reflected in their SFC values, and higher fuel mass flow rate than other tested fuel samples.

Brake Specific Energy Consumption

Brake specific fuel consumption (BSEC) is the amount of fuel consumed by the engine to produce a unit amount of work. It is a parameter used to compare fuel economy among engines with different capacities and characteristics [35]. Fig.4, shows the variation of brake specific fuel consumption of DF and various DF-MOME blends at different loads. The brake specific fuel consumption (BSEC) is seen to decreases with increase of load, which is the standard characteristic of the engine. It is desirable to obtain a lower value of BSEC meaning that the engine used less fuel to produce the same amount of work. This is one of the most important parameters to compare when testing various fuels. The BSEC in general, was found to increase with increasing proportion of biodiesel in the fuel blends; this could be due to the high mass flow of fuel entering into the engine.

In addition, the high viscosity of the blends may also inhibit the proper atomization of the fuel, which in turn affects the combustion process. For all fuel blends, BSEC is found to decrease with increase in load. This is due to the higher percentage increase in brake power with load as compared to the increase in fuel consumption. However, B5 and B10 have significantly lower BSFC compared to diesel fuel. The BSEC was observed to decrease as the load on the engine increases for all type of fuel combinations under study. The likely explanation could be that at lower loads, significant proportion of the fuel inducted through the intake does not burn completely due to lower quantity of fuel, low cylinder gas temperature, and lean fuel -air mixture. While at higher load, the cylinder wall temperature is increased, and reduces the ignition delay, improves fuel combustion and consequently reduces fuel consumption [36,37]. A significant drop in BSEC values of all tested fuel samples was observed at 2500g engine load and thereafter a slight increase in BSEC values were recorded as the load is raised to 3000g. At an engine load of 2500g, the BSEC values for B5, B10, B15, B20, and B25 fuel samples were observed to be 2.75%, 1.95%, 1.66%, 1.37% and 0.22% lower than the DF fuel benchmark (13.82MJ/kWhr). This drop in BSEC values is evident for reason that the percent increase in fuel consumption required to operate the engine is less than the percent increase in brake power. Hence, the initial decrease could be attributed to near completeness of the fuel combustion process [30]. The significant drop of BSEC values for B20 and B25 fuel samples at this critical engine loading condition, suggest the manifest influence of biodiesel, and improved lubricity of the blended fuel samples. In addition, by increasing the blend percentage, the calorific value reduces and the air-fuel ratio decreases, the fuel samples become denser and more viscous and fuel atomization less efficient. The combinations of these factors are somewhat responsible for the behaviour exhibited in Fig. 4.

Brake Thermal Efficiency

Brake thermal efficiency (BTE) is defined as the ratio of the output of the brake power to that of the chemical energy input in the form of fuel supply [35]. It is the true indication of the efficiency with which the thermodynamic input is converted into mechanical work. Fig. 5 showed the variation of the BTE with respect to load for DF and MOME –DF blends. In all cases, BTE increases with an increase in load. This can be attributed to reduction in heat loss and increase in power with increase in load. It can also observe that, blended fuel samples shows higher brake thermal efficiencies at all load conditions compared to that of diesel fuel. The initial rise in BTE values which peaks at the engine load of 2500g could be attributed to more efficient fuel combustion processes, and the additional lubricity provided by the fuel blends. At this critical engine load, it was observed that B5, B10, B15, and B20 fuel samples demonstrated higher BTE than DF benchmark (0.261%) by 2.68%, 1.91%, 1.53% and 1.15% respectively. While, B25 fuel samples displayed a BTE value similar to DF fuel sample. In a similar study conducted by Rao *et al*. [38] on the performance characteristics of neem oil methyl ester in a compression ignition engine, also revealed that the BTE of B10 and B20 fuel blends were very close to that of diesel fuel. It was also observed that as the proportion of biodiesel in the blend increases, BTE decreases noticeably on account of poor atomization of blends due to higher viscosities and lower calorific values of the blends. It has been observed that the fall in brake thermal efficiency and power output in some cases reveal that specific fuel consumption relates conversely with thermal efficiency [24]. This however, emphasized the desirability of running engines at near their maximum power output to expect good return for the burnt fuel. The falling off in thermal efficiency are due to increase mechanical losses in engine relative to useful power output, throttling losses and deterioration in combustion efficiency, and also suggests the influence of biodiesel concentration in the fuel blends on the BTE results [24, 39-41]. These unravelled results to large extent corroborates the report of Agarwal [42], and suggested that the thermal efficiency of an engine operating on biodiesel is generally better than that operating on diesel.

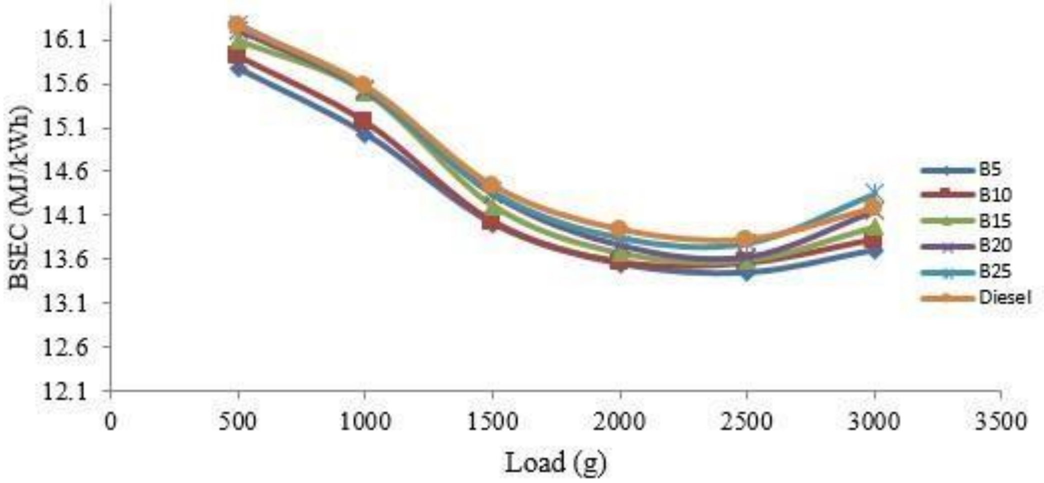

Fig.4 Variation of BSFC for DF and MOME-DF blends with increase in load

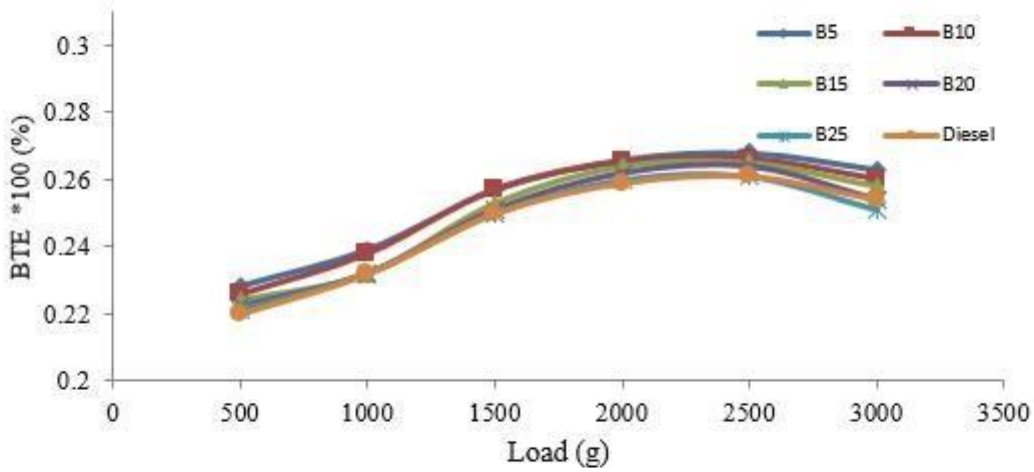

Fig. 5 Variation of BTE for DF and MOME- DF blends with increase in load

CONCLUSION

This comprehensive investigation yields critical insights into the application of marula biodiesel-diesel blends in compression ignition engines, with implications for sustainable fuel development in sub-Saharan Africa. The experimental data demonstrate that low-percentage MOME blends (B5–B15) achieve a functional equilibrium between renewable fuel content and engine performance. Specifically, the B5 blend emerged as the most efficient formulation, delivering 2.68% higher brake thermal efficiency and 18.7% lower BSFC compared to conventional diesel at 2500g load. These improvements stem from the synergistic effects of MOME's oxygenated molecular structure (enhancing combustion completeness) and its inherent lubricity (reducing mechanical losses).

The study also elucidates the thermodynamic trade-offs associated with higher biodiesel concentrations. While B20 and B25 blends maintained acceptable performance, their elevated viscosities (4.60–4.65 mm^2/s) and reduced energy densities

(42.80–43.10 MJ/kg) resulted in suboptimal atomization and combustion, particularly under high loads. This phenomenon was quantified through BSEC analysis, where B25's improvement over DF diminished to just 0.22% (vs. B5's 2.75%), underscoring the nonlinear relationship between blend ratio and energy conversion efficiency.

From a practical standpoint, these findings support the adoption of B5–B15 blends in existing diesel engines without modification, offering immediate benefits for emissions reduction and fossil fuel displacement in marula-endemic regions. Future research should focus on:

Long-term engine wear studies to validate the lubricity advantages observed in short-duration tests.

Cold-flow performance characterization, given marula biodiesel's favorable pour point (-13.75°C for crude oil).

Economic feasibility analyses of decentralized MOME production in rural African communities.

This work advances the global understanding of non-edible biodiesel applications while providing region-specific data to inform energy policies in developing economies. The demonstrated performance parity of optimized MOME blends with diesel, coupled with marula's ecological adaptability to arid climates, positions this feedstock as a strategic resource for sustainable energy transitions.

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