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European Journal of Advances in Engineering and Technology, 2017, 4 (6): 457-465

Research Article ISSN: 2394 - 658X

Influence of Marula Oil Methyl Ester–Diesel Fuel Mixtures on the Performance of a Variable Load Compression Ignition Engine

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ABSTRACT

A TD 110-TD 115 single cylinder four-stroke compression ignition engine test bed, and incorporated with a hydraulic dynamometer was used to conduct the engine performance analysis to study the influence of marula oil methyl ester (MOME)- diesel fuel(DF) on engine performance The engine performance experiments of DF samples 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 (SAE, 1995). The findings of the tests show that: the brake power reached to a maximum at 2000g engine load, and decreases slightly thereafter for all tested fuel samples. The brake power for B5 and B10 fuel samples were observed to be 0.19% and 0.094% higher than DF(2.315 kW), with B15 fuel sample exhibiting brake power value similar to DF benchmark, this could be attributed to their comparably higher fuel mass flow rate, better fuel oxygenation, and air-fuel mixtures than DF sample; the minimum brake specific fuel consumption (BSFC) values for all tested fuel samples was recorded at the engine load of 2500g, with B5 and B10 fuel samples lower than the DF benchmark (309.10 g/kWh) by 18.7% and 0.16%, thus suggesting a propensity for improved fuel economy on account of their lower fuel consumption patterns, lubricity and higher fuel mass flow rate; the drop in brake specific energy consumption (BSEC) values for B5 (2.75%), B10 (1.95%), B15(1.66%), B20(1.37%), and B25(0.22%) fuel samples were also found to be lower than the DF (13.83MJ/kWhr) benchmark, to further explains the influence of biodiesel proportion in the fuel samples, whose increase lowers the calorific values, air-fuel mixtures, and consequently raises the densities and viscosities of fuel samples with an adverse effect on fuel atomization and combustion. The combined effects of improved fuel combustion and inherent lubricity of fuel blends enabled B5 (2.68%), B10 (1.91%), B15 (1.53), and B20 (1.15%) fuel samples to exhibit higher brake thermal efficiency (BTE) values than B25 (26.1%) and DF (26.1%) samples respectively under similar loading condition. Consequently, the rise in biodiesel proportion in the blends is the culprit for poor fuel atomization and combustion behavior, which in turn serves as a pointer to higher blend viscosities and lower calorific values respectively. It could be seen from foregoing that B5, B10 and B15 MOME-DF blended fuel samples clearly demonstrated superior performance characteristics than conventional diesel fuel, and is therefore suitable for use as fuel, and diesel fuel extender and/or conserver in Nigeria.

Keywords: Marula oil methyl ester, diesel fuel, fuel mixtures, compression ignition engine, performance characteristics

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INTRODUCTION

Sclerocarya birrea (Anacardiaceae) also referred to as ‘Marula’ in English language, is a popular wild tree distributed in many African countries. The plant occurs through west, north-east and east tropical Africaacross a range of vegetation types, principally wooded grassland and dry savannah of the northern tropicalAfrica and sahelian region [1], and this include northern Nigeria. The fruit is round or oval drupe, usually widewith a diameter of 30-40 mm. The shape and number of nuts per stone determine the final shape of the fruit.According to Quin [2] and Shone [3], the seeds inside the stone can also be eaten and they have a delicate nutty taste, and a high nutritive value and high (up to 56%) oil content per kernel [4]. The energy value of the marula kernel is approximately 2 699 to 2 703 kJ per 100 g kernel [3], and the evidence of its oil high stability suggests *its* use in biomass, blending, cosmetics, and biodiesel production [5]. Marula oil contains a large proportion of monounsaturated fatty acids and natural antioxidants.

It can be classified as a high–oleic acid (70–78%) with relatively low tocopherol content. The exceptional stability is traceable to its fatty acid composition [6]. However, recent studies have mentioned that some of the minorcomponents in the oil may also be contributing to this important antioxidant property [7]. Marula oil contains a similar fatty acid composition to olive oil, but 10 times more stable to oxidation. The oil contains 67.2% oleic acid, 5.9% linoleic acid, 14.1% palmitic acid, and traces of linolenic acid [4]. Glew *et al* [6] reported that the fatty acids of marula oil accounted for 47 mg/g dry weight of the seed, two-thirds of which was oleic acid. The essential fatty acid linoleic acid was present (24.5 mg/g dry weight), but the other essential fatty acid, α-linolenic acid, was absent. The total content of sterols in marula oil was 287 mg/100 g oil, with β-sitosterol as the main compound, with about 60% of the total sterols and a high amount of Δ5-avenasterol, which was found to be 16% of the total sterols acts as an antioxidant and as an antipolymerization agent in frying oils [4].

According to Mariod and Abdelwahab [5], oils containing fatty acids of low molecular weight are slightly less viscous than oils of an equivalent degree of unsaturation containing only high-molecular-weight acids, and marulaoil was found to be less viscous (37.6 mPas) compared with sesame (57.0 mPas), groundnut (65.7 mPas) and sunflower (62.1 mPas) oils [8,9]. Oxidative stability is an important parameter for evaluating the quality of oils and fats, as it gives a good estimation of their susceptibility to oxidative deterioration, the main cause of their alteration [10]. The oxidative stability of marula oil, as measured by the Rancimat test at 120 ◦C, was 43 hours. This high oxidative stability may be due to a high percentage of monosaturated fatty acids in addition to other minor bioactive components such as sterols and phenolics [4-5]. Even though, marula oil is traditionally used in cosmetics, in food as cooking oil and as a meat preservative and to treat leather against spoilage, only few published works have demonstrated the bioenergy prospects of marula oil for compression ignition engines.

Gandure and Ketlogetswe [12] once reported that at a compression ratio of 16:1, the results of engine torque, brake power and specific fuel consumption as 27.2 Nm, 3.67 W and 0.59 g/kWh respectively for diesel fuel, and 26.3 Nm, 3.6 W, 0.34 g/kWh respectively for crude marula oil, at 80% fixed load (compression ratio of 16:1), in compression ignition engine, and the performance of crude marula oil was found to compares favourably with those of conventional diesel fuel. In addition, it was also observed that marula oil fuel recorded smooth steady increase in performance profile across all compression ratios which outperforms conventional diesel on lower compression ratios for engine torque and brake power, with a significant fuel economy better than conventional diesel fuel.

To further evaluate the bioenergy potential of marula oil, Ejilah *et al* [13] also reported on the following fuel properties of marula oil: a). The high viscosity, saponification value and oleic acid content calls for reduction of its viscosity profile to overcome anticipated engine durability challenges, while the oiliness and saponification tendencies are likely to promote better lubricity of engine parts to mitigate friction and wear; b). The relatively higher cetane number of marula oil as fuel is advantageous for efficient fuel combustion and engine performance; c). The comparatively lower heating value of marula oil could slightly affect the engine power output when compared with diesel fuel; the high flash point of marula oil used as biolubricants and biodiesel could make transportation and handling safer. While, its low pour point makes it suitable for engines at cold start and under low load condition and; d). The high oxidative stability of marula oil makes it an asset in storage, on account of the longer shelf life of its products.

Hence, to surmount the challenges of high oil viscosity, results of studies of the effect of chemical modification *via* alcoholysis on viscosity, and other fuel properties of marula oil have been investigated and reported. From the results of alkali-catalyzed ethanolysis, Ejilah *et al* [14] observed that; a higher ethyl ester (66.66%) yield occurred in KOH catalyzed ethanolysis than the results of ethyl ester (57.43%) obtained from NaOH -catalyzed reactions; the KOH catalyzed reactions generated higher ethyl ester (55.46%), higher glycerol (50.70%), and lower losses (45.56g) than its NaOH catalyzed counterpart; the transesterification process significantly reduced the viscosity of the MOEE^a (ester produced from KOH catalyst), and MOEE^b (ester produced from NaOH catalyst) biodiesel samples by 86.6% and 85.5% in comparison with viscosity of crude marula oil, but falls within the National Renewable Energy Laboratory (NREL) category of useable biodiesel fuel (i.e. 4-6 mm^2/s).

In a related study, Ejilah *et al* [15] had also recorded the following observations from alkali-catalyzed methanolysis of marula oil, that is : KOH catalyzed reactions yielded higher methyl ester (66.66%), higher glycerol (48.30%) and lower losses (36.00g) than the results of methyl ester (57.43%), glycerol (47.86%) and higher losses (45.36%) obtained from NaOH catalyzed methanolytic reactions; KOH catalyzed transesterification process produce more methyl ester yield for reasons that KOH has higher molecular weight, density and more reactive, than NaOH alkaline catalyst; the transesterification process significantly reduces the viscosity of the MOME^a, and MOME^b biodiesel samples by 87.8% and 88.5% respectively, and falls within the category of useable diesel fuel and biodiesel fuel standards; KOH catalyzed methanolysis produced biodiesel samples with higher viscosity profile than its NaOH catalyzed counterpart; and the heating value of diesel fuel was found to be higher than MOME^a, MOME^b, and marula oil respectively. Nonetheless, the heating values of MOME^a and MOME^b are 6.49% and 6.78% lower than the NREL standard (refer to table 1). Hence, it could be inferred from the aforementioned studies that the fuel properties of marula biodiesel are sufficiently in good agreement with the NREL specifications for biodiesel production, and further lends credence to its choice and usability as a prospective bioenergy feedstock in Nigeria. It is in the light of the foregoing, that this study intends to evaluate the influence of MOME –Diesel Fuel mixtures on the performance of a compression ignition engine, to achieve the objective of utilizing marula biodiesel as a diesel fuel extender and conserver in Nigeria.

DESIGN, MATERIAL, PROCEDURE, AND METHODS

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 transesterified 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 AND DISCUSSION

ENGINE PERFORMANCE ANALYSIS

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].

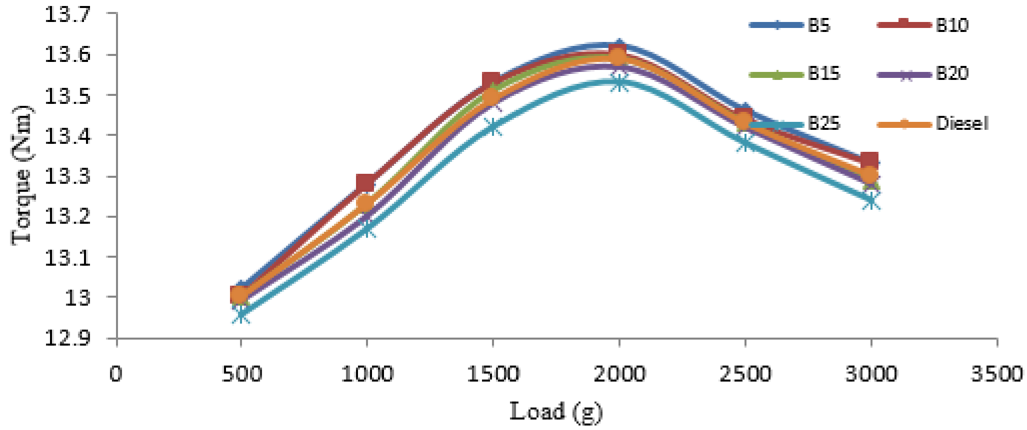

Fig. 1 Variation of brake torque for DF and MOME-DF blends with increase in load

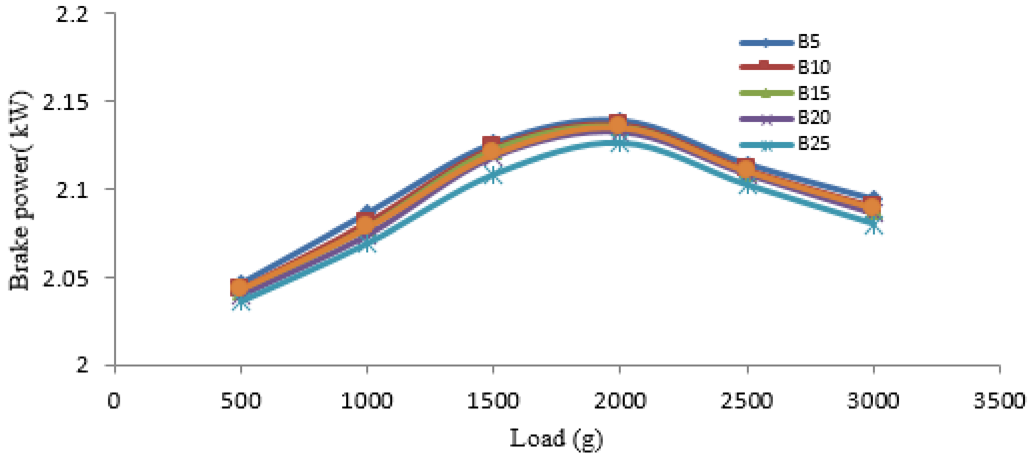

Fig.2 Variation of Brake Power for DF and MOME-DF blends with increase in load

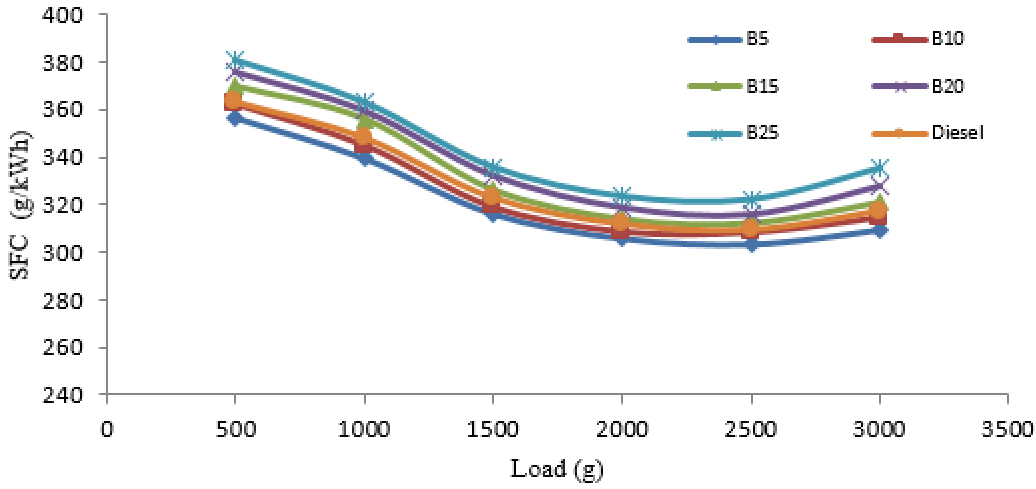

Fig. 3 Variation of SFC for DF and MOME-DF blends with increase in load

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.

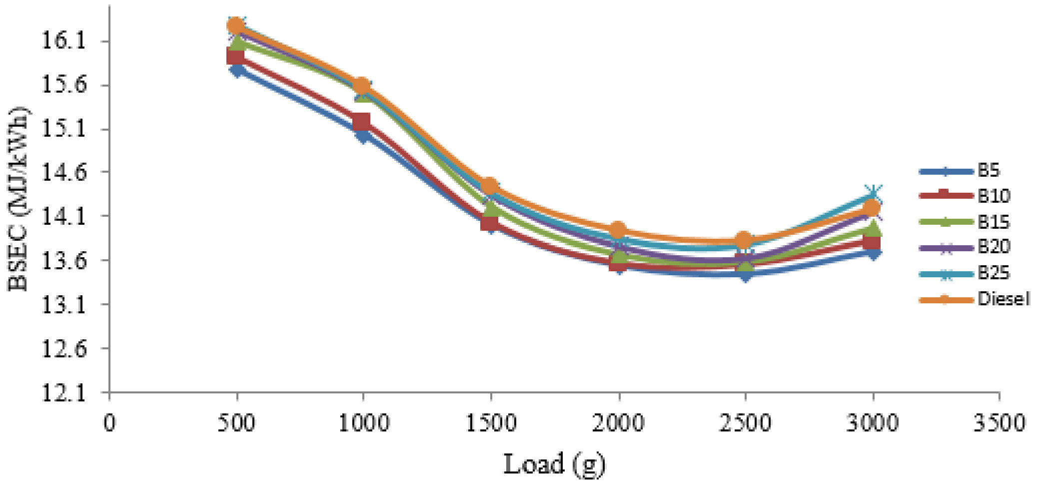

Fig.4 Variation of BSFC for DF and MOME-DF blends with increase in load

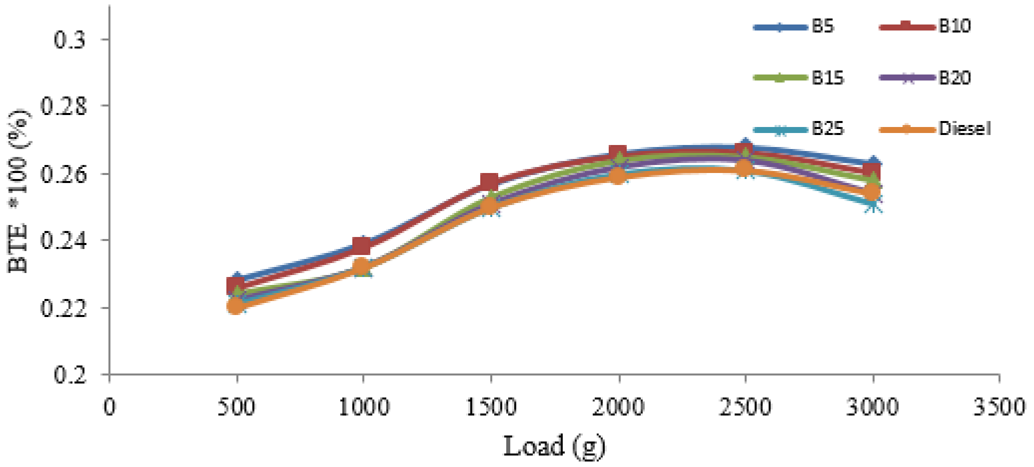

Fig. 5 Variation of BTE for DF and MOME- DF blends with increase in load

CONCLUSION

The following conclusions could be drawn in respect of the influence of marula biodiesel-diesel fuel mixtures on engine torque and brake power, brake specific fuel consumption, brake specific energy consumption, and brake thermal efficiency:

- The brake power rose to a maximum at 2000g engine load, and decreased slightly thereafter for all tested fuel samples. The brake power for B5 and B10 fuel samples is higher than the DF benchmark, 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, and air-fuel mixtures than DF sample.
- The brake powers of B20 and B25 fuel samples were observed to be lower than DF sample, on account of the comparatively lower fuel mass flow rate, and air-fuel mixtures of blended fuel samples. The slight variations in brake power for DF and blended fuel samples could be explained in terms of; their higher fuel densities and viscosities, and their consequent decrease in combustion efficiencies, poorer fuel atomization. The improved fuel oxygenation due to higher presence of biodiesel in the blended samples could also boost engine torque and brake power.
- The minimum BSFC values for all tested fuel samples was observed, with B5 and B10 fuel samples lower than the DF benchmark. B5 and B10 fuel samples exhibited a propensity for fuel economy on account of their lower fuel consumption patterns, lubricity and higher fuel mass flow rate. While, B15, B20, and B25 fuel mixtures are higher than DF sample. The influence of the volumetric presence of the biodiesel in the blend on the engine SFC behaviour could be explained in terms of the slight reduction in fuel consumption, the rise in fuel mass flow rate, drop in the heating value, increased oxygenation and lubricity of the blended mixtures respectively.
- The BSEC values for B5, B10, B15, B20, and B25 fuel samples dropped lower than the DF benchmark. The further drop in BSEC values of B20 and B25 fuel samples at 2500g load, suggest the manifest influence of higher bi-

odiesel proportion in fuel samples, which consequently lowers the calorific values, air-fuel mixture, and also raises the densities and viscosities of fuel samples with an adverse effect on fuel atomization and combustion.

- The maximum rise in BTE values at 2500g load could be attributed to improved fuel combustion performance, and additional lubricity provided by fuel blends. B5, B10, B15, and B20 fuel samples demonstrated higher BTE values than DF at same load. While, B25 fuel samples displayed a BTE value similar to DF. Furthermore, the rise in biodiesel proportion, and poor atomization of blends could be attributed to higher viscosities and lower calorific values.

Acknowledgements
The authors acknowledge the support of the Abubakar Tafawa Balewa University, Bauchi and Federal Polytechnic, Bauchi for permitting the use of their laboratory facilities for this research work.

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