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Evaluating the Fuel Potential of Castor Biodiesel and Its Blends for Land-Based Gas Turbine Engine

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ABSTRACT

The significant contributions of land-based gas turbines to the power generation sector cannot be over emphasized. However, fueling gas turbines with fossil fuels is linked to atmospheric emissions, contributing to global warming and climate change. Therefore, this research aims to investigate the potential of locally sourced castor oil as a credible biodiesel feedstock for powering land-based gas turbines. Castor seeds were locally sourced, and crude oil was produced via mechanical extraction. The physio-chemical properties of the fuels were evaluated, and both the oils and the resulting biodiesels were characterized for specific gravity, viscosity, sulfur content, and lower heating value, using ASTM standards. The sulfur content for castor oil was 0 mg/L compared to diesel's 0.73 mg/L. Castor biodiesel (COB) had a specific gravity of 0.9594, while diesel's specific gravity was 0.8536, with specific gravity increasing from B10 to B30. Thermodynamic performance of the castor biodiesel and its blends was analyzed using GASTURB software, examining specific fuel consumption (SFC), power output, fuel flow rate, thermal efficiency, and emissions. Results showed that COB and B30 had the highest power outputs of 33,839.5 kW and 33,801.9 kW, respectively. However, COB had higher SFC (0.4567 kg/kWh) and fuel flow (2.66366 kg/s) compared to diesel (0.2934 kg/kWh and 1.98875 kg/s). The findings suggest that COB fuel and its blends have potential for powering land-based gas turbines.

Keywords: Transesterification, Fuel, Physio-Chemical Properties, Gas Turbine Engine.

1 Introduction

Gas turbines have flexibility in fuel choices, including diesel and natural gas, but fossil fuels are linked to harmful emissions. Despite large deposits in some regions, the environmental impacts of fossil fuel usage, such as global warming [1], make the adoption of low-carbon, net-zero emission fuels, like biodiesel, increasingly necessary. For the environment to be preserved from the harmful release of greenhouse gases. Therefore, a deliberate emissions law has to be enacted and compulsory for engine manufacturers to change to low carbon emission designs [1],[2]. The use of low carbon neutrality and net zero emission fuels like biodiesel is the key in order to attaining this goal [3],[4]. Crude oil reserves are depleting, and the search for alternatives has driven attention to biodiesel, a renewable fuel. In 2023, global biodiesel consumption reached 65.86 million metric tons, with projections to exceed 75 million metric tons by 2030 [4]. Indonesia is the largest producer, with 13.65 billion liters in 2022, surpassing Brazil and the U.S [4]. There are various biodiesel feedstocks, including mustard oil, moringa oleifera oil, corn oil, neem oil, palm oil, linseed oil, karanja oil, algae oil, babassu oil, beef tallow, camelina oil and castor oil etc. Also, there are categories of biodiesel feedstock; first generation, second generation and third generation [5]. Castor seed falls into the second-generation feedstock category and is abundantly available in northern Nigeria, influencing its selection for this study.

Biodiesel is appealing due to its lower pollutant emissions, high flash point, good lubrication qualities, and cetane number, closely matching conventional diesel. It can be used as pure biodiesel (B100) or blended with petroleum diesel (B5–B20) at a ratio between 5–20% with minimal technical adjustments. Burning of biodiesel fuel does not contribute to a rise in the level of carbon dioxide in the atmosphere and does not pose a danger to the ozone layer [6]-[12]. The biodiesel produced from renewable resources could help to minimize the burning of fossil fuel and CO_2 production. The biofuels and bio products produced from plant biomass mitigate global warming. This resulted from the CO_2 released in burning being equal to the CO_2 absorbed by plant during photosynthesis and does not increase the net CO_2 in the atmosphere. Moreso, an increase in biodiesel production by trans-esterification may lead to an excess of glycerol production as a by-product [13]-[15]. These factors enable its usage in most diesel engines and gas turbine engine with little or no modification. Castor biodiesel was selected in this study because of high cetane, very low cloud and pour points, making it suitable for use in extreme cold weather conditions [16]-[18].

Studies have shown that gas turbine engine (GTE) power output improves slightly with biodiesel compared to fossil fuels, though at the cost of higher fuel flow rates [19]-[21]. For example, Saifuddin et al. [3] investigated bioethanol as fuel in micro-GTE. The study found that the replacement of aviation kerosene by cryogenic methane decreases CO_2 emission by more than 20% with the simultaneous increase (by a factor of 1.6) of the emissions of water vapor, HNO_2 and HNO_3. The decrease in

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NO_x emission can occur using cryogenic methane, biomethanol and bioethanol instead of kerosene. The replacement of aviation kerosene by biofuel makes it possible to decrease the soot emission. Savel'ev et al. [22] investigated biodiesel on a capstone micro turbine using a capstone software to monitor the performance of turbine running on biodiesel. It was found that the capstone gas turbine operated successfully with a biodiesel blend of up to 100% and the emissions results were very low as the NO_X and CO emissions tested low. However, NO_X was reduced by 73%. Furthermore, there was almost no Sulphur in the biodiesel, SO_X emissions were drastically reduced.

The review of the literature suggests that the use of biodiesel as alternative fuel to conventional diesel presents itself as a possible solution for powering land-based gas turbine engine with several advantages; reduced pollutant emissions, its renewable, biodegradable, non-toxic as well as its environmentally friendly nature. In this research work, castor oil was extracted and converted to biodiesel and it was used to power land-based gas turbine engine. The study further investigates the physio-chemical properties of the biodiesel oil produced and performance of GTE in relation to COB and its blends and compared with conventional diesel.

2 Materials and Methods

The primary materials used in this study were castor biodiesel and its blends (B10, B15, B20, B25, and B30), produced at Spectral Laboratory Services, Kaduna, Nigeria. Conventional biodiesel was also acquired in Kaduna, Nigeria. The raw materials for producing castor biodiesel included castor oil, methanol, sulfuric acid, sodium hydroxide, a magnetic stirrer, a conical flask, and a separating funnel [23]-[26]. Sourcing of the castor seeds and the production of castor crude oil was at the Department of Mechanical Engineering, Air Force Institute of Technology, Kaduna through mechanical oil extraction method. The mechanical screw press oil expeller was used which is more efficient than all other methods of oil extraction due to low operation cost and its high-quality light-coloured oil with low concentration of FFA [27]. The seeds were fed through the hopper, crushed and transported by a rotating screw in a press barrel. Continuous transport of feedstock by the screw shaft causes the pressure to increase to a level needed, which increases the friction inside the screw press and generates heat which lowers viscosity of the oil in the crushed seeds thereby increasing the oil flow rate. The oil and cake are usually collected at the oil outlet and press cake exit [28],[29]. The production of the castor seeds oil biodiesel was carried out at the Spectral Laboratory Services, Tudunwada, Kaduna State through transesterification process (catalytic transesterification). Transesterification involves the transformation of oil with alcohol in presence of a catalyst forming alkyl esters (biodiesel) and glycerol [30],[31].

2.1 Preparation of the biodiesel

After characterization and testing, castor oil was found to contain very high FFA. To reduce the FFA in the castor crude oil, it was first esterified. A mixture of 4000 ml of oil, 1200 ml of methanol, and hydrogen tetraoxosulphate (VI) acid was added at room temperature and stirred continuously for 30 minutes. The mixture was then left in a separating funnel for 24 hours, after which the oil layer was poured. The top layer, containing impurities, was poured into a separate container. The esterification process is illustrated in Fig. 1. The esterified oil was subsequently transesterified as shown in Fig. 2. Methoxide was prepared by dissolving 102 g of KOH in one litre of methanol. The mixture was added to 3.8 litres of oil heated to 600°C. The mixture was stirred continuously for one hour at 600°C and later transferred to a separating funnel for 24 hours. After this period, the glycerin at the bottom was poured, and the oil above was washed with deionized water three times. After the last wash, the pure biodiesel (triglyceride) was collected in a separate container for blending with synthetic diesel.

Fig. 1 Esterification process of castor oil.

Fig. 2 Transesterification process of castor oil.

The characterization and the physio-chemical properties of the fuels: B10, B15, B20, B25 and B30 were done in Spectral Laboratory Services, Tudunwada, Kaduna, and presented in Fig. 5-Fig. 9. The results from the physico-chemical analysis were in accordance with ASTM D6751 standards, which provide quality requirements for alkyl ester-based biodiesel fuels [32]. The production of the biodiesel blends was also carried out in the same Laboratory.

The gas turbine engine simulation data was obtained using Gasturb 13 software, with technical details provided in Table 1.

Table 1 Specifications of the gas turbine [33]-[36]

Manufacturer	GE
Model	LM2500
Power rating	24MW
Pressure ratio	18.75
Turbine inlet temperature	1505.5K
Mass Flow	72.5kg/s
Compression isotropic efficiency	0.87
Turbine Isotropic efficiency	0.9
Combustor pressure loss [%]	5

The simulation software interface is shown in Fig. 3. The procedure involved in putting the calorific value of castor biodiesel and its blends with conventional diesel (derived from the physico-chemical analysis) into the simulation platform. The resulting output parameters included engine power output, fuel mass flow rate, specific fuel consumption (SFC), thermal efficiency, and NO_x emissions. A flowchart illustrating this research work is presented in Fig. 4.

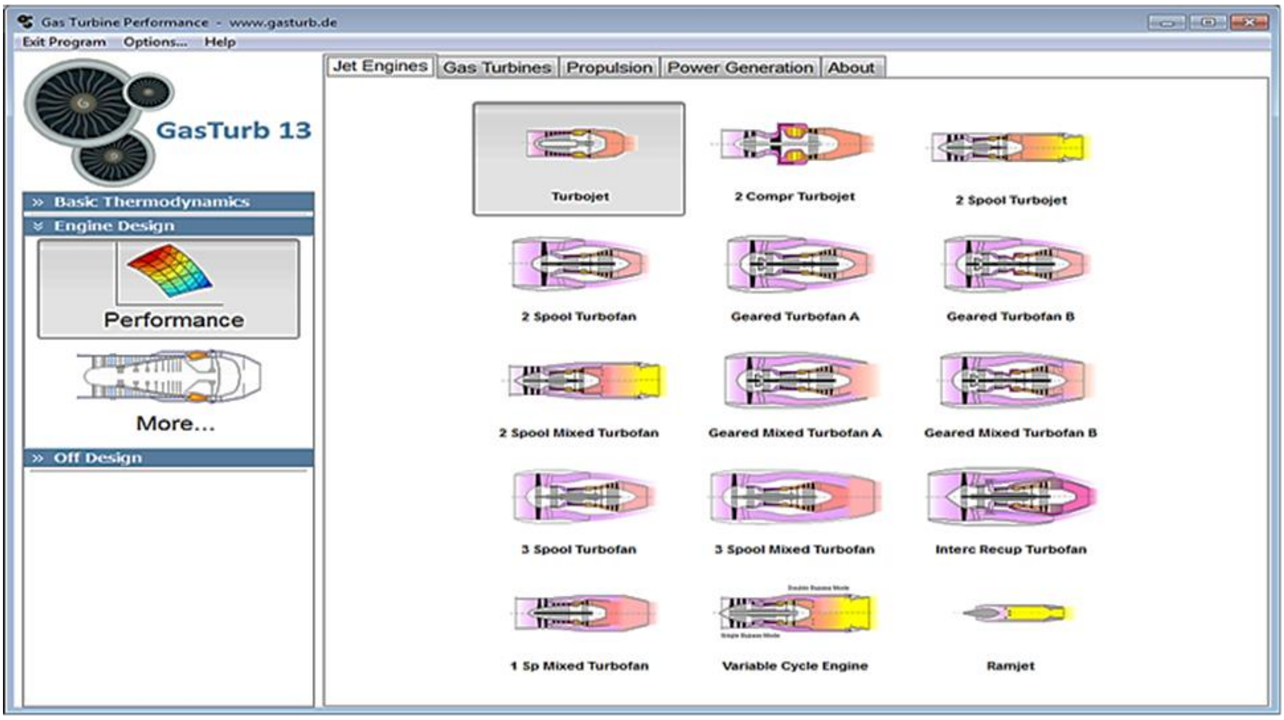

Fig. 3 Screenshot of Gasturb 13 Interface.

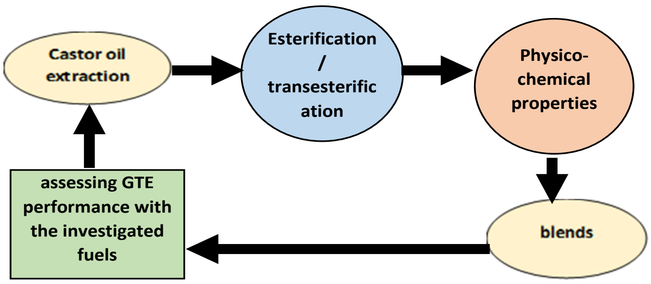

Fig. 4 Research flow chart.

2.2 Production of Biodiesel Blends

The biodiesel blends were prepared by mixing precise proportions of biodiesel with conventional diesel. For B10, 10% volume of biodiesel was mixed with 90% volume of the conventional diesel. For B15, 15% volume of biodiesel was mixed with 85% volume of the conventional diesel. For B20, 20% volume of biodiesel was mixed with 80% volume of the conventional diesel. For B25, 25% volume of biodiesel was mixed with 75% volume of the conventional diesel. For B30, 30% volume of biodiesel was mixed with 70% volume of the conventional diesel.

3 Results and Discussion

3.1 Specific gravity for the investigated fuels

The specific gravity results of the fuels are shown in Fig. 5. Specific gravity measures a fuel's density relative to water density. It was found that castor biodiesel (COB) had the highest specific gravity at 0.9594, while diesel had the lowest at 0.8536. It was also observed that the specific gravity increased with higher blend ratio, i.e., from B10-B30 (0.036%, 0.026% 0.017%, 0.013% and 0.10%). It was observed that B10-B30 has its specific gravity values below ASTM (D6751) while COB is slightly higher than ASTM value. This is due to its fatty acid configuration [20]. Furthermore, the value of 0.9594 for COB guarantees good atomization of the fuel in GTE because of its specific gravity below 1. This implies that the biodiesel fuel is less dense (lighter), hence, low fuel viscosity will help fuel jet to break up into smaller droplets sizes, and the less the viscosity of biodiesel the better for fuel atomization. Therefore, COB influences the performance of the gas turbine engine [19],[34]. The value of 0.9594 for specific gravity is comparable with value of 0.9257 observed in neem biodiesel [20].

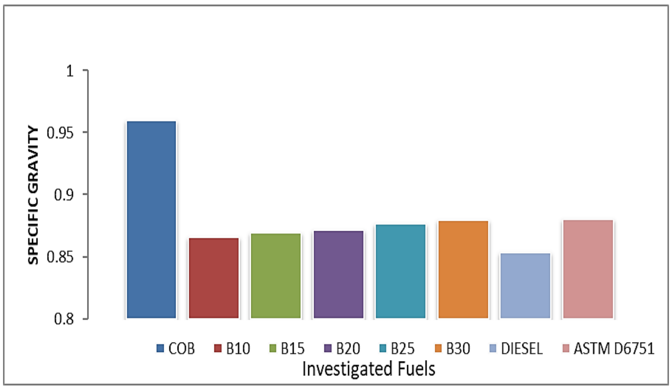

Fig. 5 Specific gravity of the investigated fuel

3.2 Sulphur content for the investigated fuels

Sulphur content results of the investigated castor biodiesel fuels and its blends are presented in Fig. 6. From the figure, it can be seen that COB showed no measurable sulphur content, implying zero SOx emissions. Sulphur content for B10 and B15 was 0.01, while B20 and B25 recorded 0.04. Diesel had a slightly higher sulphur content. Higher sulphur content is inimical to the engine because Sulphur is combustible and emitted SO_X into the atmosphere [20]. Sulphur can lead to high temperature corrosion of the blade which in turn will affect the performance of the turbine blades, causing them to lose shape and significantly impacting the turbine's efficiency. High-temperature corrosion refers to a chemical attack from gases typically at temperature above 400℃ [19]. Furthermore, COB has an advantage over diesel because COB, B10 and B15 is found to have less sulphur content, signifying lower emission to the environment. The result of sulphur content is comparable with value of 0.01 mg/l in yellow oleander biodiesel [36].

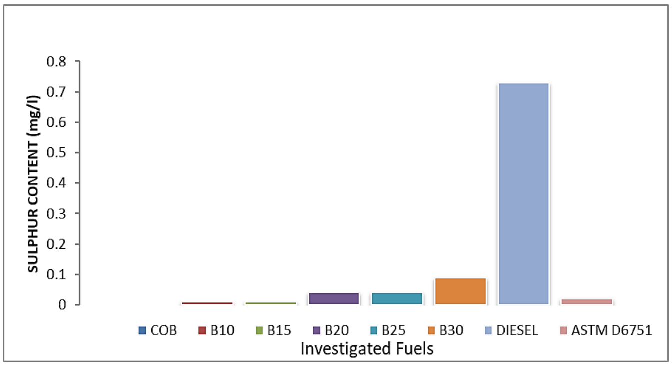

Fig. 6 Variation of sulphur content for the fuels investigated

3.3 Viscosity content for the investigated fuels

Viscosity results for the fuels are displayed in Fig. 7. Viscosity of the investigated fuel measures the oil's resistance to flow [21].

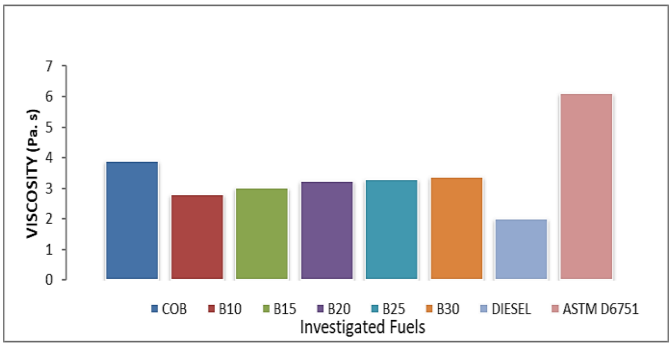

Fig. 7 Results of the viscosity content of the investigated fuels

The viscosities of COB, B10, B15, B20, B25, B30 and diesel obtained were; 3.9001, 2.8097, 3.0083, 3.2302, 3.3002, 3.3610 and 1.9952 Pa.s. and compared to the maximum value 6.1 Pa. s for ASTMB. The observation indicates that the viscosities increased with an increased blend ratio, i.e. from B10 to B30. Similarly, the values of viscosities obtained for all investigated fuels fall below the range specified by the ASTMB standard. This is attributed to the castor oil viscosity which reduced greatly during transesterification of the oil. It can also be attributed to the oil reacting with a monohydric alcohol in presence of a catalyst to give the corresponding monoalkyl esters [19]. High viscosity means that the fuel is thick and will have a negative impact on the fuel pumping because it requires more energy to pump due to increased resistance to flow. As a result, the power requirement for the pump will increase, leading to higher energy consumption [20]. Also, breakdown of fuels particles (atomization) will take long time. The obtained viscosity value for COB is similar to the value of 5.218 Pa. s in jatropha biodiesel [20].

3.4 Flash point for the investigated fuels

Fig. 8 shows the variation of the flash point obtained for the investigated fuels. Flash point is a measure of volatility and residual alcohol in the fuel, and a determinant of flammability classification of materials [33]. It provides an indication of fire risk in storage under ambient conditions. The flash point does not directly affect the performance of a gas turbine engine but it is an important parameter in terms of storage. The obtained values of the flash point of biodiesel and its blends are 20.6%, 8.47%, 8.77%, 9.06%, 9.32% and 9.80% compared to 19.1% for ASTMB standard. It was observed that COB had the highest flash point at 206℃, compared to 71℃ for diesel. This is because COB has more thermal energy needed to make it burn. In this study, the higher flash point was also an advantage in terms of fire point, this is because the oil vapours will continue to burn when ignited [18]. The result of flash point is comparable with the value of 120℃ observed in yellow oleander biodiesel [36].

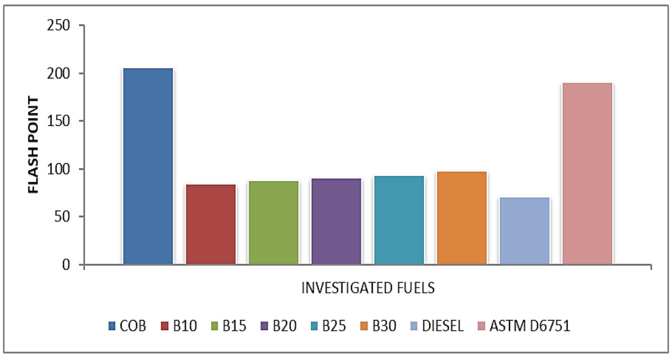

Fig. 8 Variation of flash point for the fuels investigated

3.5 Low Heating Value for the Investigated Fuels

Fig. 9 presents the low heating value (LHV) of the investigated fuels. The LHV is the measure of available thermal energy produced by a combustion of fuel [33].

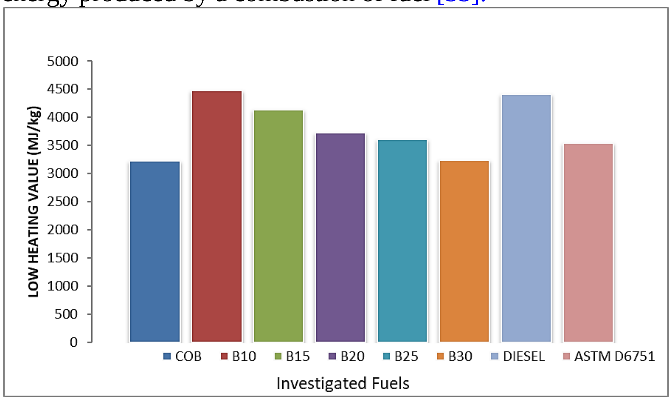

Fig. 9 Results of low heating value for the different fuels investigated

The LHV for COB, B10, B15, B20, B25, B30 and Diesel are 32.24, 44.76 ,41.30, 37.29, 36.03, 32.40 and 44.11 MJ/kg, respectively, as compared to 40 MJ/kg for ASTMB standard of COB. B10 and Diesel has the highest LHV. This indicated that the LHV for these fuels are predicted to perform well in the engine because of its higher thermal energy. From the open literature [3], when the LHV is higher the efficiency of the engine is higher [5]. On the other hand, the COB will likely consume more fuel in the engine because it has the lowest LHV. It was also found that as the blend ratio increases the LHV decreases, with COB having the lowest of 32.24 MJ/kg. This is due to transesterifying castor oil to COB which only insignificantly increased the LHV [9]. To ensure the increase of the resulting LHVs, COB has to be blend with conventional diesel. This will lead to enhancing the COB LHVs to be comparable to conventional diesel's LHV. The obtained result of the LHV in this research is comparable with value of 36.7 MJ/kg observed in neem biodiesel [20].

3.6 Results of the Performance Evaluation of the Gas Turbine Engine with the Investigated Fuels.

3.6.1 Specific fuel consumption (SFC)

Fig. 10 shows the variation of the SFC of the gas turbine with the investigated fuels. As shown in figure, the diesel has SFC of 0.2934 Kg/ kWh because of its low heating value is higher as compared to the other fuels apart from B10. The highest SFC is obtained with the COB fuel which is a result of its lower calorific value compared to that of diesel. It is also observed that the SFC drops gradually with a decrease in blend ratio of the biodiesel. This means that the mass flow rate of COB is higher than that of diesel and other blends. The implication of this result is that with COB, the engine performance will be high but not without a trade-off of higher fuel flow rate. Higher fuel flow will result in high fuel consumption and greatly impact fuel cost. This typical behaviour is similar to those observed with the value of 0.2234 Kg/ kWh in yellow oleander biodiesel [36].

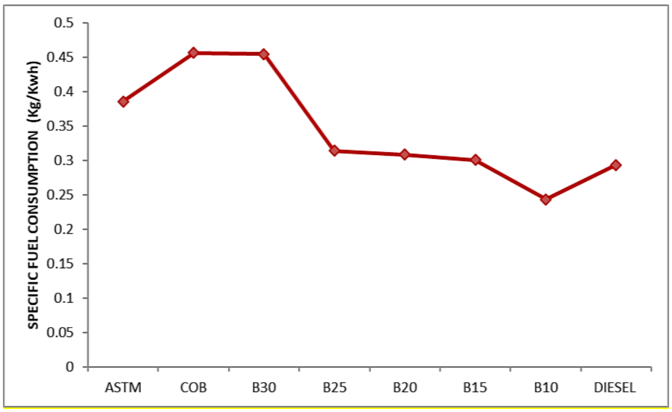

Fig. 10 Variation of SFC with the Various Fuels Investigated

3.6.2 Power output

Fig. 11 presents the result of the power output of the gas turbine engine with the investigated fuels.

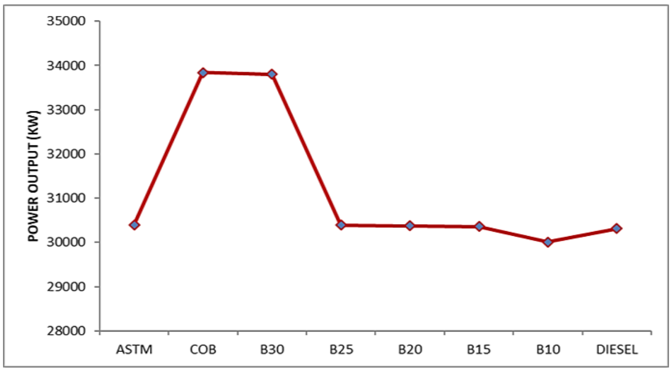

Fig. 11 Variation of power output of the various Fuels.

The values of the power output for ASTM, COB, B10, B15, B20, B25, B30 and diesel are 30397, 33839.5, 33801.9, 30387.1, 30377.4, 30361.1, 30012.8, 30312.8. It was found that the COB had higher power output of 33839.5 kW due to its fuel combustion properties such as high energy density, flash points and good auto-ignition temperatures. Other factor that contributed to higher power output was the mass flow of COB compared to diesel of 30312.8 kW. It clearly shows that the power output increases with an increase in blends ratio of the fuels. COB has the higher power output and is followed by B30, B25, B20, B15 and B10. The result of this investigation is comparable with that reported for the value of 25809.5 kW in yellow oleander biodiesel [36].

3.6.3 Mass fuel flow

Fig. 12 shows the mass flow rate of the various fuels in the gas turbine engine. The mass flow rate is a measure of the rate of the movement of passing fuels, and it is a very important parameter in GTE [7]. Mass flow rate usually is directly proportional to the SFC. It was found that as the mass flow of fuel increases, the SFC increased. It was also found that B10 had the least mass flow of fuel. This is mainly due to its specific gravity of the fuel [19], whereas COB had the highest mass flow of fuel. This would result to high SFC, which in turn increased GTE performance. The mass flow rate of the investigated fuels reduces gradually with decrease in blend ratio of the biodiesel. The result of this investigation is comparable with value of 1.66366 kg/s observed in yellow oleander biodiesel [36].

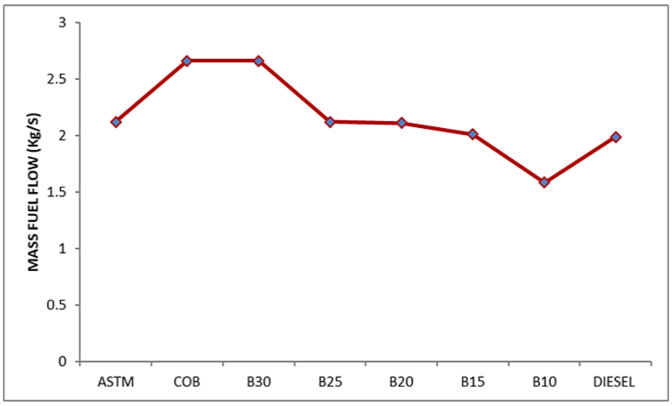

Fig. 12 Variation of mass fuel flow in the turbine of the various fuels.

3.6.4 Thermal efficiency

Thermal efficiency is the ratio of the network output to the heat input in gas turbine [37]. The input is the rate at which energy is supplied to the gas turbine, usually calculated from a measured fuel flow rate and fuel's heating value [37]. Fig. 13 shows the results of the thermal efficiency of the investigated fuels. It was observed that COB has the highest thermal efficiency than the other fuels investigated in this study. This is because of the LHV calorific value of castor biodiesel fuel that is lower than that of its blends and the diesel fuel. This implies that more heat will be giving off during combustion and turbine inlet temperature (TIT) will be increased that enhances the overall GTE performance. The increase in gas TIT will lead to an increase in the net power output of the cycle and produce higher efficiency. It was also found in Fig. 13 that as the blend's ratio decrease, the thermal efficiencies reduce. This result is comparable with value of 0.3748 observed in yellow oleander biodiesel [36].

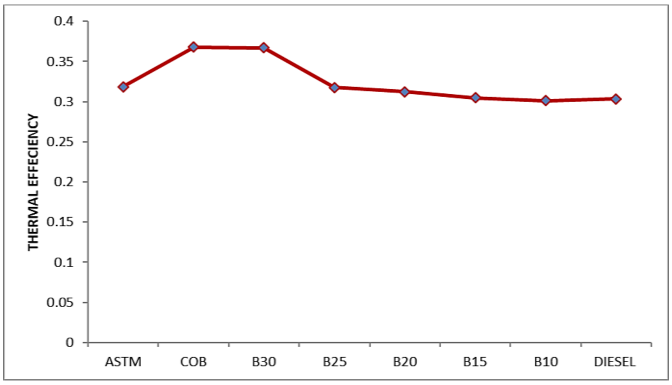

Fig. 13 Variation of thermal efficiency of the various fuels in the gas turbine

3.6.5 NOx emission

Fig. 14 shows the NO_X emissions results of the investigated fuels. The NOx is group of highly reactive gases, including nitrogen dioxide, nitrous acid and nitric acid [37]. It was found that the NO_X emissions for COB fuel has a very negligible value of 0.1 when compared to conventional diesel with high NOx emissions values of 3.8. It was also found that the NO_X emissions level increased as the blend's ratio of the fuels increased. However, NO_X was reduced by 0.037% compared to diesel because there was almost no NO_X in the biodiesel. Therefore, NO_X emissions to the environment were drastically reduced. This is due to presence of oxygen, higher combustion temperatures, and shorter ignition delay all contribute to nitrogen oxides formation [37]. The low NOx emissions results achieved in this research work show that the COB fuel is environmentally-friendly. This result is comparable with the value of 0.523ppm in yellow oleander biodiesel [36].

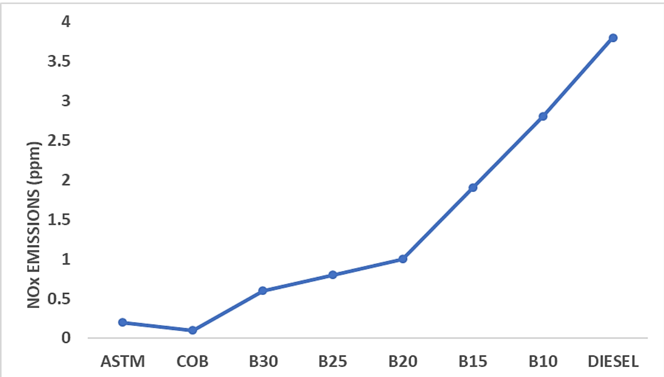

Fig. 14 Variation of NO_X emissions of the various fuels in the gas turbine

4 Conclusion

Biodiesel has gained significant global attention due to its renewable and environmentally friendly nature, driving increased production efforts in the near future. This study evaluated the potential of castor biodiesel and its blends for powering land-based gas turbine engines. Locally sourced castor seeds were mechanically processed to extract oil, which was then esterified through transesterification to produce castor biodiesel and its blends. The physio-chemical properties of the fuels were tested and found to meet ASTM standards, except for the specific gravity of castor biodiesel (COB), which was 0.9594. The specific gravity, being less than 1, ensures effective atomization of the fuel in gas turbine engines. Among the blends tested, B10 was the most recommended, as its properties consistently fell within the ASTM range across all evaluations. In terms of performance, castor biodiesel demonstrated a higher power output of 33839.5 kW compared to diesel fuel's 30312.8 kW, although at the cost of a higher mass flow rate. Importantly, NOx emissions were reduced by 0.037% compared to diesel, as biodiesel contains almost no NOx, significantly lowering environmental impact. Thus, castor biodiesel and its blends performed comparably to diesel fuel and can be considered a suitable alternative.

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