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Evaluation of the Emission and Engine Operability of Biodiesel and Biodiesel Blends Produced from Alkali-Catalyzed Esterification and Transesterification of Jatropha Oil Feedstock

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Abstract

This study reports on the engine performance analysis of biodiesel and blends produced from jatropha-based bio-oil feedstock via combined esterification and transesterification process, the physiochemical of the bio-oil, and subsequent biodiesel produced. Jatropha bio-oil was characterized to determine its fuel properties. A liquid phase transesterification reaction at 60 min reaction time, 50°C temperature, using a methanol-oil molar ratio of 40:1 and 0.35 g of sodium hydroxide (NaOH) catalyst was carried out on the conversion of jatropha bio-oil to biodiesel. The resulting biodiesel blends (B10, B20, B30, B40, and B100) were evaluated for their performance in a standard diesel engine in terms of sound level, brake-specific fuel consumption (BSFC), engine power, and fuel consumption. Furthermore, the combustion characteristics of the biodiesel blends were analyzed, leading to the assessment of gaseous emissions, including carbon monoxide (CO), hydrocarbons (HCs), carbon dioxide (CO_2), hydrogen sulfide (H_2S), nitrogen oxides (NOx) and total volatile organic carbon (TVOC). The results showed that using biodiesel made from jatropha bio-oil and its blends greatly enhanced engine performance measures in comparison to traditional diesel. However, a significant decrease in NOx, HC, SO_2, and CO emissions was observed under high load and engine speed of 1500 rpm, attributed to lower atomization, and viscosity of biofuel combustion temperatures. Lower emissions of CO and HCs were observed with a biodiesel blend percentage, indicating a cleaner combustion process. This research underscores the viability of jatropha biodiesel, and blend percentage as a sustainable alternative fuel, suggesting potential pathways for reducing reliance on fossil fuels while mitigating environmental impacts through lower emissions.

Keywords: Biodiesel, emission, engine performance, transesterification

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INTRODUCTION

The demand for fossil fuels remains high globally due to their role in energy, transportation, industrial production, power generation, and domestic heating. However, alternative energy sources, particularly biodiesel, are gaining popularity due to their renewable, biodegradable, non-toxic nature and lower pollutant emissions. Biodiesel has emerged as an environmentally friendly alternative for internal combustion engines, driven by concerns about depleting fossil fuel reserves [1–3]. There are continuous demands for fossil fuels centered in certain parts of the globe to meet the growing need for energy, transportation, industrial production, power generation, and heating required domestic usage across the globe [4–8]. The utilization of alternative energy sources is growing in popularity [6]. Due to its advantages over today's fossil fuels, including being renewable, biodegradable, non-toxic, and generating fewer pollutants, biodiesel has garnered a lot of attention lately [7]. Biodiesel as a more environmentally friendly alternative fuel for internal combustion (IC) engines has gained in popularity over time, owing to worries about the region's fossil fuel stocks decreasing [8, 12].

Among the major challenges facing the use of bio-oil feedstock to produce biodiesel as a sustainable alternative to fossil fuel these days, at least 80% of the expenses related to producing biodiesel come from bio-oil feedstock [9], which limits the scalability of biofuel, and resolving these issues is essential for its wider implementation. Biodiesel production from edible oils, traditionally used due to their low free fatty acids, presents environmental and economic advantages but also raises food versus fuel issues and negatively affects their economic viability [10]. The exploration of non-edible jatropha oil for biodiesel production has been widely reported in the literature [1]. The bio-oil has found significant applications across Iran, Australia, China, Indonesia, Mali, and Zimbabwe [11].

However, compared to other bio-oil feedstocks, the jatropha bio-oil has a very high oil content and is non-edible thus allaying concerns regarding competition as food and availability the stock [1]. Compared with hydrocarbon-diesel, the bio-oil has a lower viscosity, and energy content, which might lead to a decrease in its efficiency and an increase in fuel consumption [13, 14]. Its poor cold flow characteristics may impact cold weather performance, and its material compatibility may lead to wear and tear on engines that are not made for biodiesel [15]. Within this framework, esterification and transesterification procedures are carried out on the jatropha bio-oil extracts to help modify and improve its fuel properties, and engine performance efficiency [20].

Interest in jatropha-based bio-oil feedstocks and biodiesel has grown as people look for a fuel that burns cleaner [11]. Biodiesel must work with petroleum-based oil to achieve biofuel with varying properties suitable for other purposes [9]. The various Jatropha blends of biodiesel have also found relevant applications in automobile industries. Benz, Audi, and BMW are big manufacturers that have allowed the usage of biodiesel up to a maximum of 20% (B20) [16]. Consequently, the investigation into biodiesel produced from jatropha oil as a fuel with many benefits that has been reported in the literature, and there are certain health risks involved as regards gaseous emissions [17–19]. Investigation into jatropha biodiesel blends with petrol diesel and its performance in diesel engines, and reduction in particulate material (PM), carbon monoxide (CO), nitrogen oxides (NO_x), and unburned hydrocarbons (HCs) is still limited in the literature [21], which can lead to some health issues including headaches, respiratory irritation, lung disease, emphysema, eye irritations, appetite loss, and tooth erosion. The emission concerns on jatropha-based biodiesel feedstock are areas requiring further research investigation. Consequently, thorough research evaluating the properties, and emission performance of biodiesel produced from jatropha feedstock becomes essential. In order to determine how brake-specific fuel consumption (BSFC), it becomes imperative to investigate the physiochemical properties, emission, and engine performance of the biodiesel and blends from jatropha oil, and compare the same with existing literature. Additionally, very few studies have investigated comprehensively emission, engine performance, and break performance efficiency of biodiesel and blend produced from jatropha seed oil.

The current research explores the collection, pre-treatment and characterization of jatropha oil for its physical-chemical properties for biodiesel production via the methodology of esterification and transesterification. The study investigates the biodiesel properties, engine test, and NO_x, CO, total volatile organic compounds (TVOC), SO_2, CO_2, H_2S, and HC emissions performance of jatropha-based biodiesel blends using a new diesel-powered generator, and compared with existing literature. The comparative evaluation in BSFC of the biodiesel and blends (B10, B20, B30, B50, and B100) in an internal combustion (IC) engine were also studied, and compared with petrol-diesel (B0).

MATERIALS AND METHODS

Feedstock Collection

The bio-oil feed stock consisting of jatropha oil was purchased in pure form from LUCO Scientific Company, Benin City, Edo State, Nigeria. The reagents used for the experimentation included methanol (CH_3OH 99.8%), sulfuric acid (H_2SO_4 98%), benzene (C_6H_6 99%), absolute ethanol (C_2H_5OH 99.8%) and potassium hydroxide (KOH 99%) were purchased from Pyrex-IG Nigeria Limited, Benin City, Nigeria. All reagents used were analytical grade chemicals with high purity, thus no further purification was required.

Jatropha Oil Characterization

Prior to the biodiesel production process, the bio-oil (jatropha oil) was characterized following the ASTM standards to determine its physical and chemical properties. Determining the feedstock qualities aids in both assessing the oil's condition and determining whether additional pretreatment is necessary [12].

Experimental Procedure

Pre-Treatment Process

The acid values of crude jatropha were measured to be 17.63 mg KOH/g which was high. The pre-treatment steps were used in the production process. In this process, jatropha oil was introduced in a rotary evaporator and heated to remove moisture for 1 hour at 95°C under vacuum.

Esterification Reaction of Jatropha Oil

A liquid phase esterification was carried out using a methanol–oil molar ratio of 40:1. One hundred grams of pretreated jatropha bio-oil was measured using as electronic weighing balance. The measured oil was poured into an Erlenmeyer flask and then placed in a water bath maintained at 50°C for 30 min. Eighty grams of methanol (99.9%) was measured in a flask. Ten milliliters of sulfuric acid (H_2SO_4 98% purity) was measured using a measuring cylinder and gently poured into the methanol. The mixture was stirred continuously to ensure homogeneity. The mixture of the acid and alcohol was transferred into the heated bio-oil contained in the bath. A magnetic stirrer was introduced into the mixture of the alcohol and oil, and the Erlenmeyer flask was cocked with a rubber stopper. The sample in the Erlenmeyer flask was then placed on the stirring plate for 6 hours with a temperature of the plate maintained at 50°C and 300 rpm. After 6 hours, the mixture was removed from the magnetic stirring plate and transferred into a separating funnel, hung using a retort stand, and allowed to stand for 24 hours until two distinct layers were observed. The bottom layer containing the free fatty acid, unreacted methanol and water droplets was removed by washing over water leaving only the oil in the funnel. This oil was termed “treated jatropha bio-oil”.

Transesterification Reaction

The methanol-oil ratio was 6:1 for transesterification. The catalyst used was sodium hydroxide. 100 mL of the treated jatropha oil was measured using a measuring cylinder. The measured oil was poured into a clean dry Erlenmeyer flask and then placed on a magnetic stirrer with heating maintained at 50°C. Twenty milliliters of 99.8% methanol was measured also using another clean measuring cylinder. The methanol was poured into a clean, dry beaker. Then, 0.35 g of sodium hydroxide (NaOH) was weighed using the analytical weighing balance. The sodium hydroxide was transferred into the beaker containing the methanol to form sodium methoxide. The sodium methoxide solution in the beaker was stirred vigorously using a glass rod until the entire sodium hydroxide pellets were completely dissolved. After thorough mixing, the sodium methoxide solution was poured into the heated jatropha bio-oil. The heating and stirring of the mixture of sodium methoxide and oil at 50°C was continued for 1 hour, after which the mixture was poured into a separating funnel and allowed to stand for 18 to 24 hours for complete separation. After 18 to 24 hours, two layers were seen, the top layer being the oil and the bottom layer being the biodiesel. The glycerin layer was separated from the biodiesel by gently opening the funnel’s tap.

Separation of the Biodiesel

The biodiesel produced was separated from the acid and excess methanol by dissolving 10 g of NaCl in 10 g of distilled water. The NaCl solution was poured into the produce biodiesel and shaken gently. It was allowed to stand for 5 minutes. After 5 minutes the separating funnel tap was opened to remove the effluent from the bottom. Fresh tap water was used to wash the biodiesel. The pH of the effluent water was tested using a pH paper. The washing of the biodiesel was continued until the pH of the effluent water became neutral. Any soap that forms during the reaction process is assisted by washing. Additionally, using warm water with a gentle washing motion delays the development of emulsions and avoids the precipitation of saturated fatty acid esters.

The fatty acid methyl ester (FAME) produced was dried at 120°C. Drying of biodiesel is necessary to further remove any trace of methanol (methanol has a boiling point of 68°C) and most importantly remove moisture from the diesel [12]. The biodiesel in the separating funnel was placed in the oven. The oven was set to 120°C and the FAME was heated in the oven for 6 hours. After this heating time, it is believed that all the traces of methanol and water vapor present in the FAME had evaporated. The percentage weight per volume of alkali-base catalyst used was deduced while the percentage recovery of the biodiesel obtained after treatment by esterification was calculated using the formula reported in the literature [8, 12].

Testing and Characterization of Fatty Acid Methyl Ester

The recovered and purified methyl ester was then tested with methanol to ascertain if there was a complete reaction to FAME or if some element of monoglyceride or diglyceride was still present owing to incomplete conversion. A few drops of the methyl ester are dissolved in a small volume of methanol about 3 to 4 mL and then shaken vigorously, no layer of separation nor emulsion was observed and a homogeneous mixture was obtained confirming it to be biodiesel. The pour point, cetane number, saponification value, viscosity, and acid values for each run were determined following standard procedures in accordance to the ASTM specifications.

Biodiesel Blending

The biodiesel blending was carried out at 26°C ambient temperature. Various blends of conventional diesel and jatropha-based biodiesel were made at volumetric ratios. Different percentages of conventional diesel fuels and jatropha biodiesels are combined to create different types of biodiesel blends. Glass beakers were utilized to prepare the blended biodiesel samples of B20 (20% biodiesel, 80% conventional diesel), B30 (30% biodiesel, 70% conventional diesel), and B40 (40% biodiesel, 60% conventional diesel). To achieve homogenous blends, the samples were thoroughly mixed with a motor stirrer for 30 minutes at 2000 rpm. In addition, the blend samples were kept for characterization in vacuum-tight sampling bottles.

Conventional Diesel Engine Test

The performance evaluation of biodiesel and biodiesel blends was conducted on a one-cylinder 10.0 hp diesel engine equipped with a single phase 220 V, 15 kW alternator situated at Luco Chemical Laboratory Ltd, Benin City. The specification of the diesel engine is presented in Table 1. This engine is often used for medium-scale power generation. The test engine was directly connected to an exhaust gas detector/analyzer, a digital tachometer, and a rotameter.

To warm the engine up, it was first driven for a short while using diesel fuel before using the fuels blended with biodiesel. Prior to the engine being turned off, diesel fuel was also used. For every fuel, the same process was followed. In order to conduct engine performance tests, the engine was initially operated at full load with the throttle fully opened. Using the throttle, the engine speeds were brought to 1500 rpm at 200 rpm intervals. Fuel flow was measured by using a digital rotameter type of flow meter. Engine oil, cooling water, exhaust gas, and inlet air temperatures were measured by using a K-type thermocouple.

Table 1. Diesel engine specification.

Diesel engine parameters	Specifications
Engine type	Diesel engine
Engine size (liters)	0.232 (single cylinder)
No. of cylinder	1
Fuel type	Diesel
Phase	Single phase
Engine cycle (strokes)	4
No nozzles holes	1
Rate brake power	220 V 15 KW
Power of the engine	10 hp

Engine Emission and Performance Study

The test fuels would be exercised on the Jatropha biodiesel produced via the transesterification process. The fuels were blended by using an overhead mixer/homogenizer device at a speed of 3000 rpm for 10 min. The brake-specific fuel consumption (BSFC) and brake thermal efficiency (BTE) of the engine running on various blends of biodiesel and conventional petroleum diesel were considered during the emission analysis process. A variety of blends, including B10, B20, B30, B40, and B50, were tested with conventional diesel at constant loads (6000 W) to examine the fuel's performance and emission characteristics in compression ignition engines. An exhaust gas detector or analyzer was used to examine the engine's exhaust emissions, which included hydrocarbon (HCs), carbon monoxide (CO), nitrogen oxide (NO_x), and carbon dioxide (CO_2). At different fuel blends, the rate of fuel consumption per load was measured. The exhaust emission gases NO_x/NO, HC, H_2S, and CO were measured using a Bosch exhaust gas analyzer BEA-350. During the emissions analyses, the engine was only run at its maximum speed of 2000 rpm. BTE depicts the relationship between fuel input energy and power output. It can alternatively be expressed as the product of the lower heating value and the mass of fuel injected flow rate. Which represent the brake torque, brake power (BP), brake thermal efficiency (BTE), and BSFC, were derived. Fuel flow rate per unit output, or brake-specific fuel consumption, measures how well an engine uses the fuel that is provided to produce work.

RESULTS AND DISCUSSION

Characterization of the Jatropha Bio-oil

The physiochemical properties of the crude jatropha oil were determined via the ASTM procedure, and the results are shown in Table 2. The results show that the biodiesel has an acid value of 24.745 mg KOH/g. The amount of water and free fatty acid (FFA) in the biodiesel is indicated by the acid number.

Table 2. Physical and chemical properties of jatropha seed oil.

Properties (unit)	This Study	Hoekman et al. (2012)	ASTM Standard	EN-14214
Density (kg/m^3)	896.7	0.920	860-900	860-900
Moisture content (wt%)	0.21	NA	--	--
Flashpoint (°C)	186	240	130	101
Acid value (mg KOH/g)	24.745	38.2	--	NA
Free fatty acid (FFA) content (%)	12.3725	12.3725	NA	NA
Saponification value (mg KOH/g)	208.652	198.0	--	--
Iodine content (g I_2/100g)	108.42	94	--	--
Peroxide value (mg Eq/kg)	9.4	--	NA	NA
Cetane value	51.1	51.0	47.0	51.0
Pour point (°C)	4	NA	--	--
Yield (%)	43.5	--	NA	NA
pH	6.8	NA	--	--

The high acid value indicates that the jatropha bio-oil contains a significant quantity of moisture and FFA contents, thus requiring further processing to remove these components [12]. The value of the FFA of the crude jatropha oil was 12.745 (mg KOH). This value is significantly higher than after esterification of the crude jatropha bio-oil, the FFA reduced to 0.989 (mg KOH) indicating that the esterification process reduces FFA content in the oil. The FFA value agrees with the findings reported.

The obtained iodine value is 108.42 g I_2/100 g. In comparison to the standard levels of 95 to 107 g I_2/100 g ASTM Standard, it is comparatively high. The oil may be beneficial in the production of oil paints and as a dietary supplement because of its high iodine value, which could be attributed to its high unsaturated fatty acid concentration. The average degree of unsaturation in fats and oils is determined by the iodine value. The amount of iodine absorbed per 100 g of oil sample is represented in terms of grams. It was discovered that the oil type had very good saponification, peroxide, and iodine values, indicating that it would not create soap during the biodiesel synthesis process.

The physicochemical characteristics of jatropha bio-oil were analyzed to confirm their suitability for biodiesel synthesis through esterification and transesterification reactions. The bio-oil's flash point is 186°C, which is relatively higher than the 101 and 130 reported for the ASTM specification, and EN-14214 standard [2, 3]. However, a fuel's flash point is a crucial characteristic since a greater flash point reduces the risk of fire and makes the fuel safer to handle and transport. Specific modifications via the transesterification process are necessary to meet these standards [8, 12]. Because biodiesel typically has a higher flash point (between 55°C and 60°C) than traditional petroleum diesel, handling it is generally fairly safe. The density of the jatropha bio-oil (896.7 kg/m^3) falls within the range of density (860–900) reported for existing jatropha bio-oil feedstock in the literature [2, 3]. The cetane number was consistent with 51 reported, and in reasonable agreement with the EN-14214 specification.

Physical and Chemical Properties of Biodiesel Blend

The outline of Figure 1(a) shows the variation in viscosity and kinematic viscosities of the biodiesel and varying blends at 40°C. The elevation of the red-colored bar charts indicates a moderate kinematic viscosity (5.37 cSt) was recorded for the biodiesel produced from jatropha seed oil, while kinematic viscosities values of 5.42, 4.89, 5.00, and 5.03 cSt recorded for B10, B20, B30, B40, and B50 were significantly higher than 4.86 cSt reported for conventional diesel. However, as the blends' percentages of biodiesel rise, so do their viscosities. The viscosity and kinematic viscosity values of various biodiesel fuels along with those of the blends are very important physiochemical properties because they impact spray atomization and fuel injection equipment performance, especially at low temperatures when a fuel's fluidity is compromised by increased viscosity [12]. In addition, fuel viscosity is a direct indicator of the IC engine's ignition [8]. Inadequate fuel atomization caused by high viscosity can result in the development of soot and engine deposits.

In comparison to regular diesel fuel, the jatropha-based biodiesel fuel has a higher viscosity, which leads to poorer spray and atomization as well as increased fuel consumption. The viscosity of blended biodiesel is lower than that of diesel. The viscosities of the biodiesel produced from jatropha; B40, and B50, respectively, showed slight variation from 0.71 mPa s reported for conventional settings, while the viscosities of B10, B20, and B30, and were relatively closer to the range for hydrocarbon diesel. The viscosities of the biodiesel and the blends increase intermittently with kinematic viscosity. The highest recorded viscosity was 4.01 mPa s for jatropha biodiesel, while the viscosities for blends B40 and B50 were 1.27 and 1.48 mPa s, respectively. Other blends B10, B20, and B30 have viscosities ≤0.99 mPa s. Fuel with a lower viscosity will cause more wear and leaks, whereas fuel with a greater viscosity will create bigger droplets during infusion and release more fuel gas emissions. Every mix satisfies ASTM D6751 requirements for biodiesel viscosities. Furthermore, B30 and B40's viscosity (4.86 and 4.89, respectively) is nearly identical to that of diesel fuel. Consequently, B100 can be utilized in diesel engines without the need for any adjustments [8].

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The power of the engine and the emissions from the exhaust are directly affected by the density of biodiesel fuel. The outline of Figure 1(b) shows the variation of the density of the biodiesel blends at 30°C is 0.8608, 0.8874, 0.8710, 0.8876, 0.8938 g/cm^3, for B100, B20, B30 and B40, respectively, and conventional diesel is 0.8608 g/cm^3. The results established that the density of the biodiesel varied intermittently between 0.88 and 0.848 g/cm^3, with biodiesel recording the maximum density (0.887 g/cm^3). The densities of the biodiesel from jatropha, and biodiesel blends B10, B20, B30, B40, and B50 were relatively higher than the density of hydrocarbon-based petrol (0.8608). The specific gravity of the biodiesel blends varied slightly from the ASTM standard (0.88), with the specific gravity of B100 (0.870) significantly closest to the range.

The density value affects burning quality by varying the mass of fuel infusion. Lower density values increase the efficiency of atomization and the growth of the air-fuel proportion. Thus, we reasoned that the greater viscosity and density of the biodiesel suggest a valid ignition. Also, since the density of the biodiesel blends is relatively lower than that of regular diesel, will offset challenges associated with fuel droplets and enlargements. Since B20's density (between 0.87010 g/cm^3 and 0.8608 g/cm^3) is similar to that of diesel fuel, hence it can be used in diesel engines without modifications (Figure 1(a) and (b)).

The properties of the produced biodiesel, its blends, and conventional diesel were measured and compared to ASTM specifications, with the results shown in Table 3. The cetane number of the blends B100, B20, B30, and B40, respectively, produced is 51.02, 51.09, 51.65, 51.80, and that of the conventional diesel is 49.7. The cetane number (51.02) of the biodiesel produced from the jatropha bio-oil is significantly higher than the 49.7 reported for hydrocarbon diesel, and falls within the ASTM specification [3]. This outcome is consistent with the findings reported for conventional diesel has a cetane number ranging from 46.8 to 49.8, and biodiesel ranging from 46 to 55, biodiesel. The cetane numbers of the biodiesel blends were significantly higher than fuels preferred for improved combustion and increased braking power. This indicates that the ignition ease of biodiesel and its various blends is enhanced by an improved cetane number [8]. This improvement tends to positively influence auto-ignition and reduce ignition delays, which results in combustion starting earlier.

The lowest temperature at which fuel releases enough vapor to form a flammable mixture above its surface is known as the fuel's flash point. The conventional diesel has a flash point of 76°C, while the biodiesel blends' respective flash points are 132°C, 70°C, 73°C, and 82°C for B100, B20, B30, and B40,

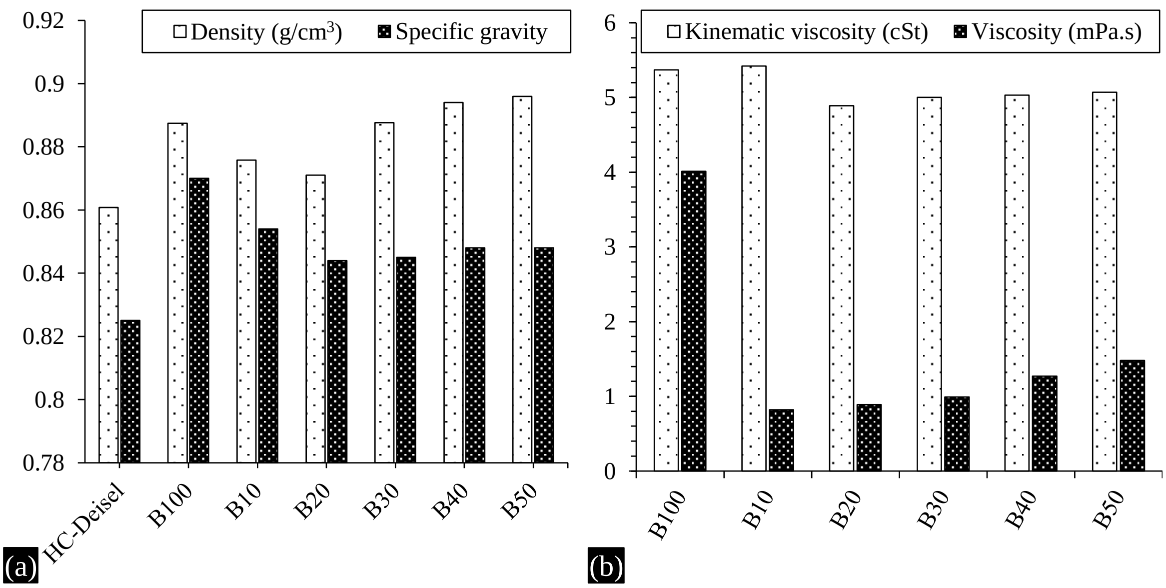

Figure 1. The variation of the blend of biodiesel properties: (a) density and specific gravity at 30°C and (b) variation of the biodiesel blend viscosity and kinematic viscosity at 40°C.

Table 3. Physical and chemical properties of produced biodiesel, blends, and conventional diesel.

Properties measured (unit)	Standard ASTM	Petrol diesel	Jatropha biodiesel (B100)	B10	B20	B30	B40	B50
Biodiesel yield (%)	NA	NA	89.54	-	-	-	-	
Density at 30°C (g/cm^3)	NA	0.8608	0.8874	0.8758	0.8710	0.8876	0.894	0.896
Specific gravity	0.88	0.825	0.870	0.854	0.844	0.845	0.848	0.848
Viscosity (mPa s)	1.9-6.0	0.71	4.01	0.82	0.89	0.99	1.27	1.48
Kinematic viscosity (cSt)	--	4.86	5.37	5.42	4.89	5.00	5.03	5.07
Flash point (ºC)	100 – 170	76	132	66	70	73	82	97
Pour point	-15 to 10	-17	-8	NA	-13.6	-	-	NA
Acid value (mg KOH/g)	< 0.8	0.35	0.504	-	-	-	-	-
Cetane number	48 – 65	49.7	51.02	51.06	51.09	51.65	51.80	-
pH	-	-	7.4	-	-	-	-	-

NA, not available.

respectively. An essential factor influencing fuel handling, transportation, and storage is the flash point. Fuels with a higher flash point are safer to store and transport. The jatropha oil-based biodiesel (B100) has a pH of 7.4, with a flash point temperature of 132°C which falls within the ASTM specification, while the blends were significantly different from the range 100°C to 170°C recommended for biodiesel. Additionally, the flash points of the blends B20 and B30 were significantly closer to 76°C reported for petrol diesel. Because biodiesel has a higher flash point than diesel blends, it can be concluded that the jatropha-based biodiesel blends are safer to store and transport [12]. The standard flash points for biodiesel in the European Union and the United States are 92°C and 120°C, respectively.

Additionally, Table 3 shows the summary of the physiochemical properties of the biodiesel and varied biodiesel blends produced from the jatropha oil via the esterification and transesterification process at an optimum biodiesel yield of 89.54% was achieved from the methyl ester conversion of 90%. Notably, the acid value of the biodiesel (0.504) was higher than the 0.35 reported for hydrocarbon-based petrol and satisfied the ASTM standard. The pour points (-8) of the B100 and subsequent blends B20 (-13.6) were significantly higher than the -15 recorded for hydrocarbon-based diesel and fell within the limits (-15 to -10) recommended by the ASTM standard. Hence, it can be concluded that the biodiesel produced and the varying blends satisfied the minimum specifications of the ASTM D6751-06.

Engine Emission Study

The principal emissions from biodiesel include smoke, sulfur oxides, nitrogen oxides, and carbon monoxide. To achieve a desired quality, biodiesel is blended with fossil fuel diesel in a precise ratio. Document number 1 outlines the preparation required to meet the specifications of ASTM document number 2. The B20 blend conforms to ASTM document number 3, while the B30 blend meets the quality requirements of ASTM D975-08.

CO Emission

Figure 2(a) shows the variation of CO emissions of biodiesel and various blends B100, B10, B20, B30, B40, and B50 at 1500 rpm engine speeds and full load. The results show that as the percentage of the biodiesel blend increases, the concentrations of CO emissions decrease, indicating improved combustion efficiency. The concentrations of CO emitted correspond to 0.083 ppm, 0.062 ppm, 0.047 ppm, 0.033 ppm, 0.02 ppm, and 0.011 ppm, respectively, for the diesel and biodiesel blends. The findings established that blends (B10–B100) show lower CO emissions than diesel (B0), highlighting biodiesel's potential to reduce CO emissions. This outcome is influenced by several variables, including the jatropha-oil-based biodiesel contains lower aromatic content than diesel and more oxygen than diesel can contribute to reduced CO emissions. The high viscosity and surface tension probably enhance the biofuel atomization leading to improved combustion efficiency and reduced CO emissions. Because biodiesel has a higher oxygen concentration than other fuels, it burns more carbon molecules and completes combustion as the amount of biodiesel in the blend increases. Moreover, the low aromatic content of the mixtures may help reduce CO emissions. In this context, the heavily premixed charge is uniformly distributed throughout the cylinder, including the boundary layer and crevice regions near the cylinder walls. In these areas, it is challenging for the fuel to fully oxidize, which can lead to significant CO emissions. Therefore, the results proved that the presence of a biofuel-rich petrol-diesel mixture at high loads leads to a noticeable reduction in CO emissions compared to pure diesel fuel, as observed in this study.

The outline of Figure 2(a) also shows the variation of hydrocarbon (HC) emissions of the blends of biodiesel produced from the transesterification jatropha-based biodiesel B0, B10, B20, B30, B40, and B50 at 1500 rpm engine speeds and full load. The outcome proved that HC emission decreased with increasing biodiesel blend percentage. The concentration of HC emitted corresponds to 0.016 ppm, 0.014 ppm, 0.011 ppm, 0.006 ppm, and 0.002 ppm respectively for the biodiesel blends (B10–B40), which were significantly lesser than diesel B0, this is probably due to physiochemical properties such as higher oxygen content and lower aromatic content recorded while a potentially near zero HC emission was recorded with higher blend percentage (B50). These results confirmed an optimum blend percentage of B50 improved combustion efficiency and were more effective in reducing HC emission, which is advantageous in environmental benefits in line with the sustainable development goal.

The result recorded total volatile organic compound (TVOC) indicates an intermittent increase in concentrations of TVOC emitted. Although increased TVOC emission may indicate incomplete combustion, and pose environmental concerns with regards to air pollution and health effects. The higher emission occurred at higher blend percentages B40 and B50, which were significantly higher than that of diesel (B0), and lower biodiesel blends, while lesser TVOC was recorded for intermediate blend percentage B20. This outcome indicates a possible change in combustion chemistry, and probably engine conditions of full load (2000 W) and engine speed (2000 rpm) due to the volatility of the biodiesel which can contribute to increased TVOC emission. However, it can be inferred from the results that biodiesel blend intermediate (B20) offers the optimum TVOC emission reduction.

The hydrogen sulfide (H_2S) emission across all the biodiesel blends (B10–B50) is extremely low at near zero limits confirming the efficient combustion process, and the absence of sulfur content in the jatropha-based biodiesel. The low sulfur content indicates the compliance of the blends with regulatory standards, the European Union’s Industrial Emission Directive (2010/75/EU), and the California Air Resources Board. This outcome confirmed the suitability of the blends across the sub-Saharan Africa border, Europe, and America.

The circular shapes within the chart in Figure 2(b) illustrate the distribution of SO_2, NO_x, and CO_2 emissions in different blends generated by the Jatropha-based biodiesel when the engine operates at a full load of 2000 W and a speed of 1500 rpm. The exterior circle indicates the varying proportion of CO_2 emission across the biodiesel blends (B0–B50). The curvature of the outer circle in Figure 2(b) in proved that CO_2 emission decreases with an increase in biodiesel blend percentage. The biodiesel blends (B10–B50) show varying degrees of CO_2 emission reduction. Higher blends (B40, B50) offer better CO_2 emission compared to other blends with pure biodiesel (B100) emitting the least CO_2. This outcome indicates efficient combustion efficiency occurs in the engine chamber with reduced hydrocarbon diesel consumption. The outcome confirmed compliance of the biodiesel blends to Environmental Protection Agency Greenhouse Gas Emission Standards, European Union’s Climate and Energy Framework (2030), and California Air Resources Board regulations.

However, the middle concentric circle represents the variation of NO_x emissions for various blends of biodiesel. The findings on the NO_x emission increase intermittently with increasing blend percentage. Although pure biodiesel B100 recorded significantly lower NO_x emissions than B20–B50, the biodiesel

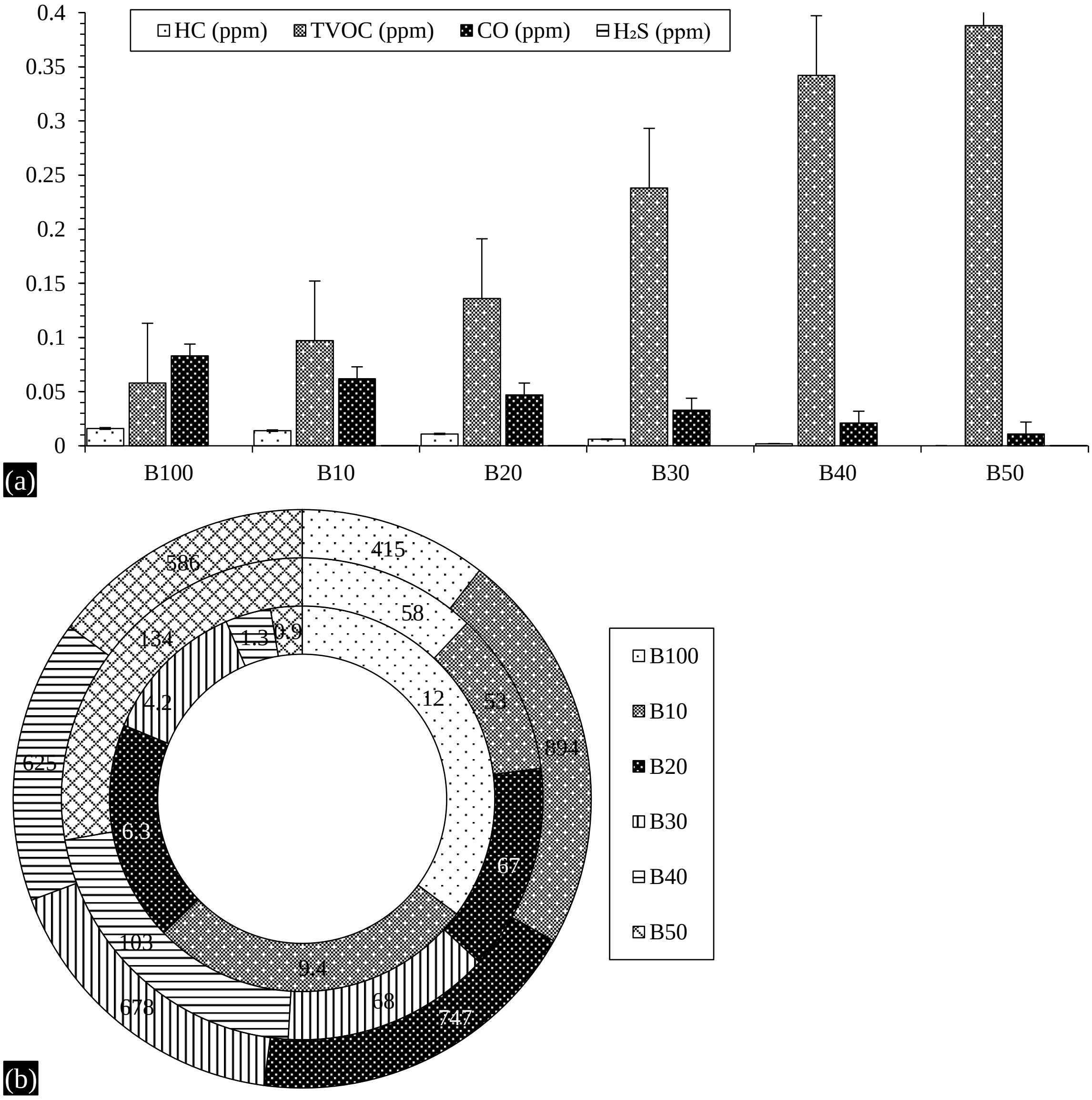

Figure 2. Variation of emissions at 1500 rpm engine speeds, and 2000 W engine load for (a) gases (hydrocarbons [HC], carbon monoxide [CO], hydrogen sulfide [H_2S], total volatile organic compounds [TVOC]) emissions of various biodiesel blends, and (b) variation of CO_2, NO_x, and SO_2 emissions of various biodiesel blends.

blend B10 recorded lower emissions than HC-diesel. The higher NO_x emissions can be ascribed to increasing cetane number associated with the B20–B50 blends percentage and combustion temperature under full load 2000 W, and high speed of 1500 rpm.

The low NO_x emission associated with B100 and B10 can be attributed to lower aromatic content in the jatropha-based biodiesel which promotes oxygenation thus reducing thermal NO_x formation, with reduced peak combustion temperature. This outcome is consistent with the findings recorded in the physiochemical properties of the jatropha biodiesel produced. The lower NO_x concentration emitted by blend percentage B100–B40 were significantly ≤120 ppm recommended for diesel engines, or pure biodiesel offers a lower blend B10 (200 ppm, 210 ppm) recommended for European Union's Stage V standard, and ≤150 ppm California Air Resources Board regulation for diesel engine. Thus, it can be inferred from the analysis that a lower blend percentage, B10, or pure biodiesel (B100) offers lesser NO_x emission reductions.

The outline of the inner circle confirmed that SO_2 emission also decreased with an increase in biodiesel blend percentage. The outcome confirmed that the biodiesel blend significantly reduced the SO_2 emission, with considerable near-zero emissions achieved at higher blends (B40 and B50). The low SO_2 emission recorded can be attributed to the low sulfur content in the jatropha-based biodiesel, which reduced sulfur oxidation during combustion. It can thus be inferred from the results that a higher blend has a low SO_2 emission, indicating its high tendency to reduce corrosion and wear on engine components. However, the significant reduction in SO_2 emissions suggests compliance with stringent environmental regulations: Environmental Protection Agency tier 4 standard (≤10 ppm), European Union's Stage V standards (≤10 ppm SO_2), and California Air Resources Board regulations (≤5 ppm SO_2), respectively (Figure 2(a) and (b)).

Performance Test on Internal Combustion Engine

Another crucial factor is engine performance, which broadly encompasses braking power, brake thermal efficiency, sound effect, and fuel consumption unique to the brakes. With a particular emphasis on brake power and brake-specific fuel consumption (BSFC), this section provides a thorough review of the performance characteristics of a diesel engine employing biodiesel and diesel blends. Table 4 shows the results of the analysis carried out at 1500 rpm engine speed and 2000 W.

Effect of Biodiesel blends on Brake-Specific Fuel Consumption and Sound Level

The results in Table 4 display the BSFC content for the various diesel and biodiesel mixes. The jatropha biodiesel's BSFC ratings dramatically drop as engine brake power rises with an increasing blend percentage (B20–B50). The results demonstrate that pure Jatropha biodiesel (B100) has the lowest BSFC, while petrol diesel records the highest BSFC output. This outcome is probably due to the changing oxygen contents, varying atomization, and spray characteristics associated with the blends and pure Jatropha biodiesel. The engine optimization proved that B100 recorded a 75% reduction, and the lower blend percentage B20 yielded a 28.8% reduction compared to B50 yielded a 57.10% reduction. The lower BSFC recorded for the pure jatropha-oil-based biodiesel indicates better engine performance compared to the blends and petrol-diesel, thus indicating reduced fuel consumption, and lower. Additionally, the low BSFC of the biofuel and blends will benefit the environment by reducing greenhouse gas emissions. The engine performance optimization will require B50 with the higher efficiency of BSFC reduction to function more effectively.

The results on the sound level confirmed that engine sound level increases with biodiesel blend percentages. Petrol diesel B0 recorded the lowest sound level, while biodiesel bend (B50) recorded the highest sound level compared to pure biodiesel (B100) and other blend percentages (B20–B40). When comparing the BSFC parameter between pure diesel and higher blends, the latter has a higher kinematic viscosity and burns at lower loads, indicating a larger mass consumption per unit of power production. Previous studies have indicated that as the biodiesel blend ratio is raised, the fuel's higher BSFC can be linked to its high density and low calorific value. The increased sound level associated with the blends translates to higher engine stress resulting from possible increased fuel density and viscosity. Jatropha oil is more densely used than diesel fuel, which leads to higher consumption. The higher density and viscosity

Table 4. Summary of results of performance test (brake power (BP), fuel consumption (FC), and brake specific fuel consumption (BSFC)) with biodiesel blends.

Blend	FC (kg/h)	BP	BSFC (kg/kWh)	Sound (dB)	LEL (%)
B0	3.0492	19492.5	0.156	95	
B20	2.1983	19780.9	0.111	106.7	0
B30	1.6173	19513.4	0.083	108.6	0
B40	1.5850	20777.0	0.076	110.2	0
B50	1.4110	20886.7	0.067	113.5	0
B100	0.8921	21735.2	0.038	99.5	0

can contribute to higher combustion pressure at the given temperature of the engine calibration. Based on the findings in Table 4, it can be concluded that a lower biodiesel blend percentage of B20 is needed for engine optimization to achieve quieter operation. The performance test study evaluated the brake power (BP) variation of different diesel blends (B10, B20, B30, B40, and B50) under constant engine speed (1500 rpm) and full load conditions (2000 W). The results proved that the value of the breaking force of the various biodiesel blend percentages varies. The pure biodiesel B100 has the highest braking force. This outcome probably results from diesel fuel losing some of its heating value when biodiesel is added to the diesel. The outcome is consistent with the findings reported.

CONCLUSION

Biodiesel's potential to meet global energy demand and reduce dependence on imported fossil fuels has positioned it as a desirable renewable energy source. This research assesses the effects of various blends on internal combustion engines and compares them with conventional diesel to identify the optimal blend for internal combustion engine performance. The B10 and B20 flash points 40°C are nearly identical. The viscosities of B10 and B20, which are 0.82 and 0.89 mPa, respectively, are nearly identical to those of the diesel fuel (0.71 mPa). The emission characteristics of CO, and HC, for biodiesel and its blends were lower than those for diesel throughout the experiment which makes it a cleaner fuel. Overall, biodiesel and its blends have been shown to emit lower levels of H_2S, NO_x, CO, and HC compared to diesel, indicating potential benefits for air quality. Biodiesel-diesel blends have higher NO_x emissions than diesel due to oxygen and cetane content. Engine performance, especially concerning the impact of additives on both engine performance and emissions, should be carefully considered.

Authorship Contributions

A.M.: Conceptualization, investigation, resources, data curation, software, visualization, writing of original draft, writing and reviewing of the manuscript. *O.E.O.:* Investigation, data curation, software, visualization, writing of original draft, writing and reviewing of the manuscript.

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Declaration of Competing Interest

The authors declare no competing financial interest. The authors also declare no conflict of interest.

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