J Ther Eng, Vol. 11, No. 1, pp. 1–15, January, 2025

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000899

Research Article

Nano-additive blends examination of performance and emission profile of CI engines fuelled with waste cooking oil based-biodiesel

Samson K. FASOGBON[1,2*], Sunday O. OYEDEPO[3]

[1]*Department of Mechanical Engineering, University of Ibadan, Ibadan, 200005, Nigeria*
[2]*Centre for Petroleum, Energy Economics and Law University of Ibadan, Ibadan, 200005, Nigeria*
[3]*Department of Mechanical & Biomedical Engineering, Bells University, Ota, 112104, Nigeria*

ARTICLE INFO

Article history
Received: 25 May 2022
Revised: 22 October 2023
Accepted: 25 November 2023

Keywords:
Aluminum Oxide Nano-additive; Compression Ignition Engines; Emission; Performance; Waste Cooking Oil

ABSTRACT

Waste Cooking Oil (WCO) could become the alternative raw material for biodiesel production to sustain energy globally. Fossil diesel causes emissions of dangerous gases in compression ignition engines, and this had led to the use of biodiesel in the engines to reduce hazardous emissions. Researchers have also used nano additives with biodiesels to further improve CI engine performance and emission characteristics; behaviors are however Fuels-Nano additives combinations specific. This work therefore studied CI engines on the combination effects of blends of diesel, waste cooking oil-based biodiesel: B0 to B100 at 10 % incremental step, and aluminum oxide (Al_2O_3) nanoparticles additive with dosages of 5 g/l and 10g/l on each fuel blends. The biodiesel was produced through the transesterification process in the presence of potassium methoxide as a catalyst. All mixtures containing nano additives were ultrasonicated at a frequency of 25 Hz to prevent agglomeration. The experiment was carried out in a four-stroke, single-cylinder, air-cooled compression ignition engine at engine speeds of 500, 1000, 1500, and 2000 rpm. The result showed a decrease in the CO emissions, brake-specific fuel consumption, and an increase in NOx emissions, brake power, and brake thermal efficiency when the percentage of biodiesel increased for pure biodiesel-diesel blend at higher engine speeds. Blends containing 5 g/l and 10 g/l aluminum oxide (Al_2O_3) Nano-additive showed a significant increase in brake power, brake thermal efficiency and a significant decrease in brake-specific fuel consumption, CO and NOx emissions. For all blends tested, (B20+10 g/l) showed the best result for performance and emissions at all investigated speeds and torques; as it gave Highest BP of 8.5 % for low speed of 500 RPM and 9.7 % for high speed of 2000 RPM, Highest BTE of 19.4 % at high-speed of 2000 RPM and Highest NOx reduction of 42.9 % at low engine torque of 25 Nm and 32 % NOx reduction at high engine torque of 100 Nm; Highest CO reduction of 28.6 % at low engine torque of 25 Nm and 20.6 % NOx reduction at high engine torque of 100 Nm. In conclusion, for better performance and emission characteristics, waste cooking oil-based biodiesel blend with aluminum oxide; B20 +10 g/l can be used to fuel the compression ignition engine.

Cite this article as: Fasogbon SK, Oyedepo SO. Nano-additive blends examination of performance and emission profile of CI engines fuelled with waste cooking oil based-biodiesel. J Ther Eng 2025;11(1):1–15.

***Corresponding author.**
*E-mail address: kolasogbon@gmail.com

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University Press, İstanbul, Turkey

INTRODUCTION

Fossil fuels are largely used in compression ignition engine; it happens to be a naturally existing substance. The need for replacement of fossil fuels has been an issue to look into due to the dangerous emission in compression ignition engines. In addition, the demand for fossil fuels is continuously increasing globally there by resulting in a rapid depletion of fossil fuels deposits [1 An internal combustion engine (ICE) is a type of heat engine that uses an oxidizer (usually air) and a combustion chamber that is a part of the working fluid flow circuit to burn fuel. The internal combustion engine's rotor, nozzle, turbine blades, and pistons are frequently subjected to direct force from the expansion of the high-temperature, high-pressure gases created during the combustion process. This force transfers chemical energy into mechanical energy that can be used to move the component across a distance [2].

Ahmad et al., and Carraretto et al., recalled that Diesel engines are compression ignition engines which are usually used to power various types of vehicles such as: Automobiles, Trains, Ships and Airplanes. They are also used to power Irrigation pumps and in an extension used to produce electric power. Combustions of fossil diesel in theses engines produce emissions that have serious negative effect on the ecosystem and the human health. To overcome these problems, global effort exists to develop clean substitute fuels that are easily available and technically feasible [3,4].

According to Demirbas, renewable energy sources have demonstrated a high potential for availability, and biodiesel has become the most widely used alternative fuel to fossil diesel [5]. On the other hand, Palash et al., Mofijur et al., and Mofijur et al. observed that the use of biodiesel in CI engines is met with certain limitations, such as a slight decrease in brake-specific fuel consumption, slightly poor fuel atomization, marginally higher density, lower cloud and pour points, piston ring sticking, issues with cold starting, and higher NOX emission [6–8]. On the other hand, Kadarohman et al. found that the limitations of biodiesel can be addressed by using certain fuel modification techniques, such as the addition of fuel additives like nanoparticles or the use of hybrid fuel [9]. Shaafi and Velraj et al., revealed that among the recent fuel modification methods, nanoparticles additions have emerged to be novel and promising; thus, many researchers have investigated the impacts of nano additives addition on the performance and emission characteristics of Internal combustion engines [10–18].

Produced from vegetable oil and other organic materials, biodiesel is an alternative fuel that bears a lot of similarities to fossil diesel. It operates in the current diesel engines using a fuel based on vegetable oil (soy or canola oil), with no changes in hardware. Transesterification is one way to produce biodiesel. The increasing demand for fossil fuels has led to a greater awareness of how quickly they are depleting. This means that using an effective and less polluting diesel fuel substitute will be necessary to address its effects. Because of its benefits to the environment and economy, biodiesel has been the fuel of choice for diesel engines during the past 20 years. Still a lot of work has to be done for further enhancement of biodiesel as a fuel.

Raghuveer et al. and Chen et al. produced biodiesels from palm kernel, the biodiesel produced by them was made through base-catalyzed transesterification of the palm kernel oil with alcohol [19, 47]. Fatty acids are gotten from the transesterification process, which is then converted to alkyl esters through acid catalysis. Non-edible Jatropha oil was also employed by Anand and Sadhik to produce biodiesel through standard transesterification process [20]. They made use of viscometer to determine the kinematic viscosity of the fuel blends at c, and also carried out a density check through the use of digital density meter. Avagyan et al. also analyzed the benefits of algae for biodiesel production and sustainable development; and submitted that Microalgae biomass production has accounted for 65–85% of the overall cost of biofuel [21]. They also analyzed microalgae and macro algae cultivation and harvesting, with a description of the complexities involved in algal biofuel production. Keskin et al. investigated fuel additives impact on Biodiesel; and reported that metallic fuel additives improved the pour point and viscosity values properties of biodiesel [22]. The Datura biodiesel is a perfect replacement to diesel because this is derived from indigenous sources and is renewable. Nevertheless, due to its high viscosity and lower calorific value, it cannot be used directly in the diesel engine [23].

Many researchers have also conducted studies regarding the impact of fuel additives and on engine combustion, performance, and emission characteristics, according to Taghizadeh-Alisaraei, Rezaei-Asl, and Devarajan et al. [24, 48]. Shaafi and Velraj, for example, investigated the combustion, performance, and emission characteristics of an engine running on two modified fuel blends: D80SBD15E4S1 (diesel-soybean oil-based biodiesel-ethanol blends) and B20 (diesel-soybean oil-based biodiesel), with alumina (Al_2O_3) acting as a nano-additive. It was noticed that the cylinder pressure arising from combustion and the heat release rate were higher than those of diesel fuel. The presence of oxygen in the soybean oil-based biodiesel and the better mixing capabilities of the nano particles must have been responsible for the reduction of CO and UHC; and slight increase of NOx at full load condition [25]. Gumus et al. looked into the effects of adding nanoparticles of cupric oxide (CuO) and alumina to fossil-diesel fuels. Additionally, the impacts of the additives on engine emissions and performance were examined. By including the nanoparticles, the characteristics of storage and combustion were enhanced. By adding alumina and cupric oxide to pure diesel, engine torque and brake power output were also marginally boosted [26]. Another study by Guru et al. empirically investigated the impact of adding copper, magnesium, manganese, and calcium to diesel fuel on quality of fuel ignition, efficiency, and pollution. Along with the amounts of pollutants including SO_2, CO_2, and CO, they also looked at the number of fuels in two scenarios: pure diesel and diesel with additives [27].

Researchers have specifically studied a number of performance parameters. Debbarma and Misra, for example, fueled compression ignition engines (CIE) using a blend of neat diesel (ND) and iron nanoparticles (INP) [28]. The results showed that the brake specific fuel consumption (BSFC) decreased by 1.55% for ND+INP and 2.71% for PB20+INP, while the brake thermal efficiency (BTE) increased by 2.06% for PB20+INP and roughly 0.36% for ND+INP. Experimental research on cerium oxide-mahua oil was conducted by Ramarao and Bharathkumar on a single-cylinder, air-cooled, four-stroke direct injection diesel engine [29]. Brake specific energy consumption (BSEC), exhaust gas temperature (EGT), and brake thermal efficiency (BTE) were among the metrics used to assess the performance characteristics. When the load was increased, the mahua biodiesel-Ce02 blend's BTE was found to be at its maximum, and at lesser loads, it tended to decrease. Praveen et al. [30] conducted an experimental study to assess the efficiency and emission characteristics of compression ignition engines using exhaust gas recirculation (EGR) and mixes of Calophyllum and Inophyllum biodiesel with TiO2 nanoadditives. A volumetric technique was used to combine 20% of Calophyllum Inophyllum biodiesel with 80% diesel (B20) to create the Calophyllum Inophyllum biodiesel-diesel blend. The outcome revealed a notable decrease in exhaust gas circulation as well as an increase in brake thermal efficiency.

Fasogbon and Asere studied the effects of soybean methyl ester on the performance characteristics of compression ignition engine, they ran the CI engine on various biodiesel-petrol diesel blends (0/100, 10/90, 20/80, 30/70 and 40/60), they found out the performance of CI engine was the best at B20 (blend 20/80) [2]. Praveen et al studied the effect of biodiesel-diesel fuel blend on compression ignition engine [30]. The study showed that the biodiesel-diesel fuel blend decreased engine performance and increased its emission characteristics. Gurusala and Selvan experimented the emissions characteristics of a compression ignition (CI) engine fueled with waste chicken fat biodiesel with alumina nanoparticles as an additive [31]. They observed a significant reduction in hydrocarbons and carbon monoxide emissions after the experiment. Fasogbon studied environmental friendliness of melon oil methyl ester in internal combustion engines; with the findings that the fuel is a near perfect environmentally friendly one [32]. Pradipta et al; 2022 assessed combustion characteristics of a 4-stroke compression ignition dual-fuel engine using a blend of diesel-Karanja biodiesel with variations of engine loadings. With the result that, the dual-fuel fired engine, indicates apex point of net heat release rate and marginal cylinder pressure curve from top dead centre. And the highest peak cylinder pressure recorded for Diesel-5DEE-PG (6.68 MPa) at 15° after TDC, as compared to Diesel only (6.11 MPa) at 9° after TDC [33].

El-seesy et al studied the Influence of Multi-Walled Carbon Nanotubes Additives into non-edible biodiesel-diesel fuel blends on Diesel engine performance and emissions, they found out that multi walled nanotube helps to improve engine performance parameters [34]. Pandian et al. investigated the effect of TiO2 nanoparticles on mahua biodiesel (BD100) at 100ppm (BD100T100) and 200 ppm (BD100T200); it was observed that (BD100T200) gave a reduction of 9.3% for CO, 5.8% for HC, 6.6% for NO and 2.7% for a smoke when compared to neat mahua biodiesel [35]. Anand et al. demonstrated that engine performance and emissions were significantly improved when 25 to 50 ppm of alumina nanoparticles, with a size of 51 nm, were added to Jatropha biodiesel fuel [36]. Arock-iasamy et al. tested the impact of a nanoparticle additive at a dosage level of 30 ppm in Jatropha biodiesel using a single cylinder diesel engine. Using neat diesel as the basis fuel, performance and emission parameters were examined. The findings showed a 9% decrease in NOx emissions, a 17% decrease in smoke opacity, a 33% decrease in HC emissions, and a 20% decrease in CO emissions. Additionally, the research revealed a 5% increase in brake thermal efficiency [12]. Sadhik and Anand combined carbon nanotube at 25, 50, and 100 ppm with a Jatropha methyl ester water emulsion. With a single cylinder diesel engine, they were able to reduce NOx emissions by 29% and smoke emissions by 28% [37]. An experimental examination was conducted by Sadhik et al. and Amit on alumina nanoparticles blended at 25 and 50 ppm in a water diesel emulsion. Along with a little drop in HC and CO emissions, there was a notable 40% reduction in smoke opacity and a 27% reduction in NOx [38, 39 The performance and emissions characteristics of a diesel engine running on a diesel-soybean oil -based biodiesel mix B20 with alumina (Al_2O_3) as the nano additive were investigated by Ojeda et al. and Shaafi et al. The discovery was made that the biodiesel derived from soybean oil had higher cylinder pressure and heat release rate than diesel fuel. This led to the hypothesis that the reductions in CO and HC emissions were caused by the oxygen present in the biodiesel and the enhanced mixing abilities of the nanoparticles [40, 41].

Hoseini et al., studied, the effects of graphene oxide (GO) nano-particles on power, exhaust gas temperature (EGT), carbon monoxide (CO), carbon dioxide (CO2), unburned hydrocarbons (UHCs), and nitrogen oxides (NOx), of a diesel engine fueled with Oenothera lamarckiana biodiesel. With the results that GO inclusion increases power and EGT significantly. It also significantly reduces CO (~5%–22%) and UHCs (~17%–26%); but slightly increases CO2 (~7%–11%) and NOx (~4%–9%) emissions [42]. Junshuai LvORCID et al., reviewed and summarized the recent research progress of nanoparticles as additives for diesel-biodiesel fuel blends. They described in detail the excellent properties of nanoparticles, and summarized

/ discussed the preparation methods. Additionally, they examined the effects of a number of widely used nanoparticles on the performance of combustion and emissions of harmful substances, including CO, NOx, UHC, and emissions from brake-specific fuel consumption, as well as the effects of diesel-biodiesel fuel blends. They also talked about the effects of nano-additives on internal combustion engines, the environment, and human health. This paper's work can make a significant contribution to the fuel industry's use of nanomaterials. The authors of the study arrived at the conclusion that their research could facilitate the effective selection of appropriate nano-additives for internal combustion engines, hence promoting low-emission features and efficient combustion [43]. Devaraj et al., discussed the effect of nano particles on engines performance and emission parameters and engine life in their paper. The paper also discussed the effect of different size and dosage of nano particles on diesel engine behaviour; and the preparation of nanofluid, several characterization methods and enhancement of biodiesel stability via various techniques [44].

Burning fossil fuels in the presence of an oxidizer, such as air, releases damaging greenhouse gas (GHG) emissions in addition to converting the chemical energy in molecular bonds into mechanical energy that can be used. Vehicles powered by lithium-ion batteries and hydrogen are two of the several green transportation options that are soon to be available. Researchers have however investigated the potential of nanoparticles fuel additives as a possible solution the harmful greenhouse gas emission. Previous studies in this direction however show that extensive fundamental and applied studies have been done on impacts of addition of cerium oxide, iron-strontium, graphene and copper to biodiesel and its blends on performance, combustion, and the reactivity of the resulting emission by internal combustion engines. Literature is sparse on the inclusion of alumina nanoparticles in biodiesel and its blends with diesel. To this end, this paper contributorily studied the effect of alumina (Al_2O_3) nanoparticles as an additive to diesel-biodiesel blends on the performance and emissions characteristics of a compression ignition engine. Future study can however investigate the toxicity of nanoparticles. The Cost analyses of nanoparticles inclusions should also be investigated vis a vis one hundred percent CO_2 taxed fossil fuels and other alternative 'renewable' fuels.

MATERIALS AND METHODS

Experimental Setup

The test engine is a four-stroke single cylinder, direct injection, air cooled Compression Ignition engine; and the detail of the engine specification employed is as shown in Table 1. The engine was run under ambient temperature of 22 ^{O}C and atmospheric pressure of 878 Mbar. In order to determine and measure the engine load and torque, the Diesel engine employed was directly coupled to an eddy current dynamometer as shown in the Figure 1. A mobile AVL flue gas analyzer was used to determine the emission characteristics of the combustion products (Table 1).

Table 1. Test engine specifications (Kama; air cooled diesel engine)

Engine Variables	The values
Combustion System	Direct Injection
No of Cylinder	Single Cylinder
Max Output	2.8 kW - 3.1kW
Con Output	2.5 kW - 2.8kW
Engine Speed	500 rpm - 2000 rpm
Bore X Stroke	70 mm x 55 mm
Fuel Used	Light Diesel Oil
Displacement	0.211
Fuel Tank Capacity	2.5 L
Starting System	Recoil or Electric Starter

Emission Analyzer AVL DITEST GAS 1000, Mobile petrol/gas emission tester, Emission diagnostics of HC, CO, CO2, O2, NOx, and lambda.

Figure 1. A pictorial view of the experiment setup.

1- Compression ignition engine
2- Eddy current dynamometer
3- Exhaust gas analyzer
4- Galvanometer

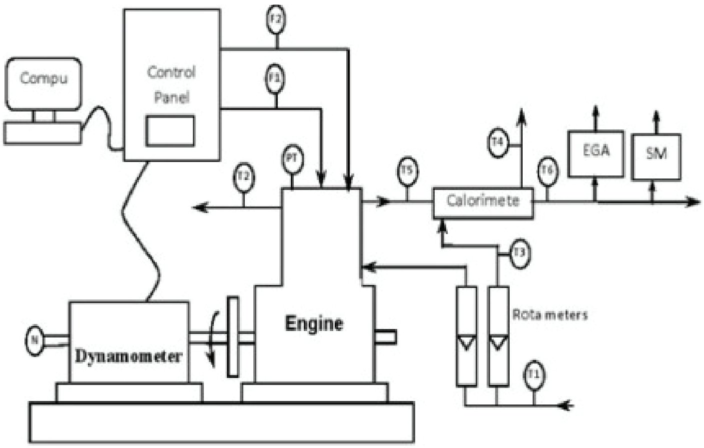
Fuel Preparation

In this experiment, a 250 mL conical flask was filled with 10.5 mL of used cooking oil, which was measured and heated to 50 °C. Potassium hydroxide pellet (0.25 g; catalyst concentration of 0.5 percent) and methanol (63 mL; mole ratio of oil to methanol of 1: 6) were combined to create a potassium methoxide solution inside the 250 mL conical flask. After vigorous stirring, the potassium hydroxide pellet completely dissolved in the fluid. After heating the potassium methoxide solution to 60 degrees Celsius, it was added to warm leftover frying oil and vigorously stirred with a stirrer for 50 minutes. The mixture was left to settle for 24 hours in a separating funnel. After that, warm water was used to wash the biodiesel in order to remove any last bits of soap and glycerol from the funnel. This was carried out up until the biodiesel was covered by the clear water in the separating funnel. The aluminum oxide and biodiesel-diesel fuel mixes were combined in an ultrasonicator to create the nano additive fuel blend. By dispersing the nano additive throughout the base fuel using the ultrasonicator technique, the nano additive was able to return to the nanoscale range. As illustrated in Figure 2, the nano additive particles were weighed to a predefined mass fraction of 5 g/l and then distributed throughout the biodiesel-diesel for 15 to 30 minutes using an ultrasonicator set to a frequency of 25 kHz. The same process was repeated for the mass fraction of 10 g/l to prepare the aluminum oxide-biodiesel fuel blends fraction of 10 g/l to prepare the aluminum oxide-biodiesel fuel blends. The density, Flash point, Cetane Index and Calorific value of each fuel blends were determined immediately after the fuel preparations according to ASTM standard. Table 2 and 3 presents the all-fuel blends properties measured according to ASTM standard guidelines. Stability of each fuel-blends was 3 h after preparation.

Figure 2. Pictorial view of blends in the ultrasonicator.

Experimental Procedure

The engine was run for 10 minutes for each blend to ensure the removal of remnants in the fuel line. After the initial analysis and error detection, some of the tests were repeated. The amount of flywheel power (P) available in the engine flywheel (brake power) is equal to P ¼ 2pTN/60000 (kW), where T (Nm) is torque available in the flywheel and N (rpm) is the engine speed. The experiments in this work were conducted on four engine speeds of 500 rpm, 1000 rpm, 1500 rpm, and 2000 rpm under full load with three replicates. The torque, power, fuel consumption, ambient temperature, ambient pressure, and environmental humidity were recorded during each test. Following the automatic recording of torque and engine speed by the dynamometer with a connected control panel, the engine power is calculated. The output torque and engine rotation speed have a significant impact on the engine power. The amount of gasoline (measured in grams) needed to generate one kW-hour of real work in the engine is known as specific



PT Pressure Transducer
N Rotary encoder
Wt Weight
F1 Fuel flow
F2 Air flow
F3 Jacket water flow
F4 Calorimeter water flow
T1 Jacket water inlet temperature
T2 Jacket water outlet temperature
T3 Calorimeter water inlet temperature = T1
T4 Calorimeter water outlet temperature
T5 Exhaust gas to calorimeter tempera
T6 Exhaust gas from calorimeter temperature

Figure 3. Experimental test engine rig.

Table 4. The accuracies of the measurements and the uncertainties in the calculated results

Variables	Measurement Boundary	Precision	Uncertainties
Density	0.60 – 3.5 g/cm^3	±0.0001 g/cm^3	±0.004
Temperature	0 – 1000 ^{O}C	±1 ^{O}C	±0.1
Cetane index	120 min	-	±0.01
Calorific value	0 – 100000 kJ/kg	±1 kJ/kg	±0.1
BTE	0 – 100 %	-	±0.02
CO	0-15.0 vol %	±0.01 vol %	±0.07
NO_X	5000 ppm vol.	±1 ppm vol.	±0.1
Speed	0 – 2000 rpm	±5 rpm	±0.05
Torque	0 – 100 Nm	±0.05 Nm	±0.05
Power	0 – 85 kW	±0.02 kW	±0.07
Flow Rate	0.1 – 35 l/hr	±0.02 l/hr	±0.07

fuel consumption (SFC, g/kWh). The dynamometer and exhaust gas analyzer readings were obtained three times to cut down on error. Figure 3 depicts the engine test rig.

Uncertainty Analysis

It is inevitable that each measurement you take, regardless of how accurate your instrument is, will have some degree of uncertainty. A measurement's uncertainty is constrained by the measuring device's accuracy and precision as well as any additional variables that can influence the experimenter's capacity to perform the measurement.

Measurement = (measured value ± standard uncertainty) unit of measurement. (1)

where the ± standard uncertainty indicates approximately a 68% confidence interval

$$\text{Relative Uncertainty} = \frac{uncertainty}{measured\ quantity} \quad (2)$$

$$\text{Relative Error} = \frac{measured\ value - expected\ value}{expected\ value} \quad (3)$$

When we report the average value of *N* measurements, the uncertainty we should associate with this average value is the standard deviation of the mean, often called the standard error (SE).

$$\sigma = \frac{s}{\sqrt{N}} \quad (4)$$

The precisions and uncertainties in the variables measured are as shown in Table 4.

RESULTS AND DISCUSSION

Fuel Blends Characterizations

The determined physicochemical properties of the produced WFO based biodiesel and its blends are as stated in Table 2, while that of of WFO based biodiesel blends and Al_2O_3 Nano additives are as stated in Table 3. It could be seen in Table 2 that as the percentage composition of the biodiesel increases in the earlier part 0 - 40 % increase, the density increases, cetane index increases, while the flash point decreases. For the percentage composition of the biodiesel higher than 40 %, the density decreases, cetane index increases and flash point increases. For all the blends B0,

Table 2. Physicochemical properties of biodiesel and its blends

Properties	Method	B0	B10	B20	B30	B40	B50	B60	B70	B80	B90	B100 (Tested)	B100 (Standard)
Density at 15.56 °C kg/m^3	ASTM D-4052	830.2	856.5	855.7	856.6	893.1	848.9	845.1	841.2	837.4	833.5	829.7	-
Flash point °C	ASTM D-92	72	69	60	62	78	95	111	225	143	160	176	130
Cetane index	ASTM D-976	60.21	60.54	60.72	62.12	62.34	62.55	62.77	62.99	63.21	63.42	63.64	47 min
Calorific value kJ/kg	ASTM D-224	47107	47022	43954	43325	43255	43185	43115	43045	42975	42905	42835	48500

Table 3. Physicochemical properties of biodiesel blends and Al_2O_3 nano additives

Properties	Method	B0 (Diesel)	B0+5g/l	B0+10g/l	B10	B10+5g/l	B10+10g/l	B20	B20+5g/l	B20+10g/l	B0 (Standard)
Density at 15.56 °C kg/m^3	ASTM D-4052	830.2	830.0	829.9	856.5	856.2	856.1	855.7	855.5	855.2	860-900
Flash point °C	ASTM D-92	72	72.1	72.3	69	69.2	69.3	60	60.3	60.4	248
Cetane index	ASTM D-976	60.21	60.22	60.24	59.54	59.56	59.58	60.72	60.74	60.76	55
Calorific value kJ/kg	ASTM D-224	47107	47108	47109	47022	47023	47023	43954	43956	43956	45500

B10 and B20 tested in Table 3, as the percentage composition of Al_2O_3 Nano additives increases from 0 g/l, 5 g/l and 10 g/l, both the Density and Cetane index decrease, while Flash point the calorific value increase. These observations in the blend's properties are in tandem with the works of Rao and Dash, 2016 [46] and Hosseini et al., 2017 [49].

Engine Performance Parameters

Plot of BSFC against speed for pure biodiesel-diesel blends

Figure 4 shows the graph of brake specific fuel consumption against engine speed for biodiesel-diesel blends. Increase in blend ratio leads to an increase in brake specific fuel consumption, this could be as a result of the high density, high viscosity and low calorific value of the biodiesel. The lower calorific value of the biodiesel, could have led to more fuel being injected into the combustion chamber during combustion; thereby leading to a rise in the amount of fuel consumed. The high density and viscosity make the atomization of the fuel slower, thus leading to an increase in the amount of fuel injected into the combustion chamber simultaneously. At each engine speed, it was observed that pure biodiesel has maximum specific fuel consumption while diesel fuel has the lowest specific fuel consumption. These results corroborate the works of Aalam and Saravanan; 2015 [11], Bet-Moushoul et al., 2016 [16] and El-Seesy et al., 2018 [18].

Plot of BSFC against speed when 5g/l of aluminum-oxide was introduced blends

The brake specific fuel consumption decreased when aluminum oxide nano-additive Al_2O_3 was introduced in the blend as shown in Figure 4. It is suspected that abundance oxygen in the lattice structure of the additive could have aided the BSFC decrease during combustion. The introduction of 5g of Al_2O_3 to the blends B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100, led to a BSFC decrease of 20%, 19.4%, 14.7% ,11,04%, 12.6% 16.4% 14.7% 13.7% 13.6% 4.9% 5.1% at low engine speed (500 RPM) and a decrease of 31.7% 30.4% 32.2% 30.2% 28.1% 33.8% 31.7% 30.4% 23.0% 15.1% 14.1% at high engine speed (2000 RPM). These results follow the works of Arockiasamy and Anand, 2015 [12], Debbarma and Misra, 2018 [17] and Anand and Sadhik, 2013 [19].

The concentration of aluminum oxide nano additive in the blend affects the brake specific fuel consumption, the higher the concentration of the nano additive the less the BSFC. Figure 5 shows that the dose of 10g/l of Al_2O_3 led to a further reduction of the brake specific fuel consumption compared to the case of 5g/l dose. This observation is likely to have been due to the availability of more oxygen

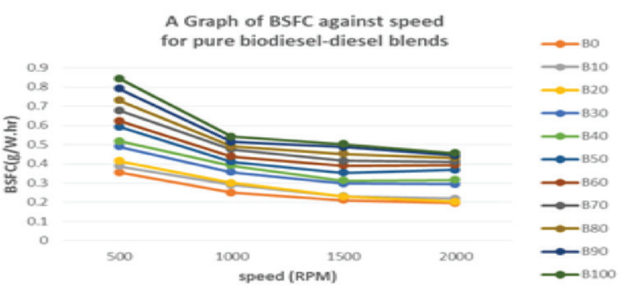


Figure 4. A graph of BSFC against speed for pure biodiesel-diesel blends.

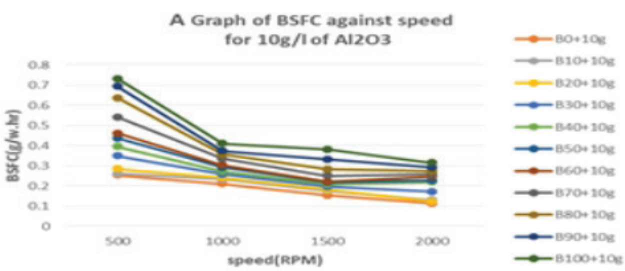


Figure 5. A graph of BSFC against speed when 10g/l of aluminum oxide was introduced blends.

for combustion. At low engine speed (500 RPM), there was a decrease of 29%, 32.6%, 31.8%, 28.8%, 23.6%, 26.6%, 26.1%, 20.1%, 13.0%, 12.5% and 13.4% for blends B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100 when 10g of Al2O3 was added and at high engine speed (2000 RPM), 42.5%, 37.3%, 39.6%, 41.8%, 30.9%, 38.5%, 37.6%, 36.7% ,34.5% and 31.0% reduction was seen for blends. These results agree with the works of Shaafi and Velraj, 2015 [25], Gumus et al., 2015 [26] and Debbarma and Misra, 2018 [28].

Plot of Brake power against speed for pure biodiesel-diesel blends

The behaviour of brake power is shown in Figure 6. The waste cooking oil-based biodiesel and its blends exhibit similar characteristics as the diesel fuel. The brake power decreases with an increasing amount of biodiesel in the fuel mixture, this could have been due to high density, viscosity and low calorific value of the biodiesel. The high density and viscosity of the biodiesel reduce the efficiency of the combustion process there by leading to a decrease in the brake power. The behaviours follow the works of Rao, 2016 [29], Gurusala and Selvan, 2015 [31], Sadhik and Anand, 2010 [35] and EL-Seesy, et al., 2018 [53].

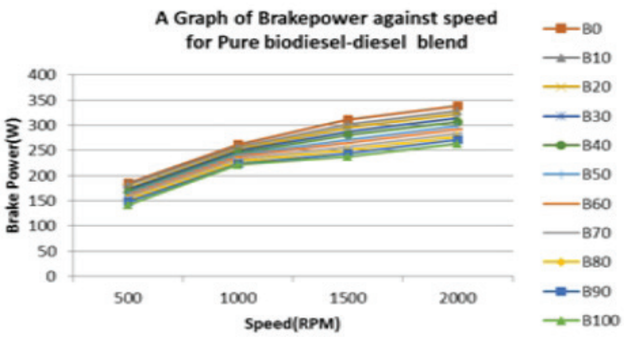


Figure 6. A graph of Brake power against speed for pure biodiesel-diesel blends.

Plot of Brake power against speed when 5g/l of aluminum oxide was introduced blends

The brake power of the engine showed a significant rise when Al_2O_3 was added is shown in Figure 7, this could be as a result of the availability of oxygen in the lattice of Al_2O_3 which enhanced the efficiency of combustion in the chamber. As performance of the engine got better, torque and speed of the engine improved, this led to an increase in the brake power of the blends B0, B10, B20, B30, B40, B50, B60, B70. The blends B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100 showed an increase of 0.88%, 0.47%, 4.2%, 0.76%, 0.54%, 0.63%, 0.87%, 0.57%, 0.39%, 0.51%, 1.6% at low engine speed (500 RPM) and 0.95, 0.74%, 6.6%, 0.98%, 0.78%, 0.86%, 0.75%, 0.68%, 0.93%, 0.63%, 1.0% at high engine speed (2000 RPM). Praveen, 2018 [30], The works of Pandian, 2017 [34], Sadhik and Anand, 2012 [37] and Ghanbari, et al., 2017 (54) corroborates this work.

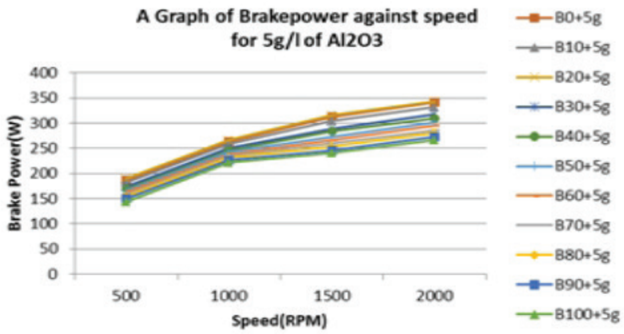


Figure 7. A graph of Brake power against speed when 5g/l of aluminum oxide was introduced blends.

A graph of Brake power against speed when 10g/l of aluminum oxide was introduced blends

Figure 8 explains the 10g/l nano-additive effect of aluminum oxide on brake power. The concentration of 10g/l of Al_2O_3 showed a further improvement in the brake power of the blends compared to 5g/l concentration. The catalytic nature of the nano additive helps the combustion to take place at lower activation energy. As a result of this, the engine was able to operate at a higher speed and torque. The blends B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100, showed an increase of 2.1%, 1.7%, 8.5%, 1.5%, 1.7%, 1.6%, 1.4%, 1.71%, 1.57%, 2.5% and 2.6% at low engine speed (500 RPM) and 2.0%, 1.8%, 9.7%, 2.0%, 1.6%, 2.3%, 1.7%, 1.8%, 1.7%, 1.9% and 2.9% at high speed (2000 RPM). The observation is inline with the works of Amit, 2015 [38], Shaafi and Velraj, 2015 [41], Rao and Dash, 2016 [46] and Gumus, et al., 2016 [55].

A graph of BTE against speed for pure biodiesel-diesel blends

As shown in Figure 9, the brake thermal efficiency of the blends increases with increase in the blend ratio, this

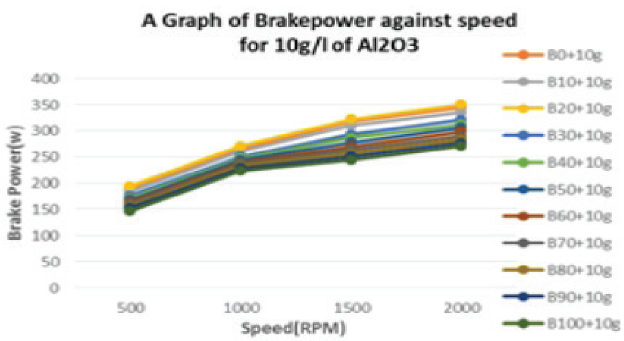


Figure 8. A graph of Brake power against speed when 10g/l of aluminum oxide was introduced blends.

is as a result of increase in brake power developed as speed increased. Brake thermal efficiency and shows a direct relationship with brake power and an inverse relationship with BSFC and calorific value. As a result of this the brake thermal efficiency is higher for low brake specific fuel consumption. The blends (B0, B10, B20, B30, B40, B50, B60, B70, B80, B90, B100) had efficiencies 6.7%, 6.25%, 5.94%, 5.13%, 4.94%, 4.38%, 4.24%, 3.98%, 3.76%, 3.54% and 3.34%, at low engine speed (500 RPM) and 12.02%, 11.01%, 11.9%, 8.61%, 7.57%, 7.04%, 6.71%, 6.56% and 6.37% at high engine speed (2000 RPM). The findings follow favourably with the works of Ojeda et al., 2015 [40], Abdel-Razek et al., 2017 [45], Sadhik and Anand, 2010 [47] and Hoseini, et al., 2018 [56].

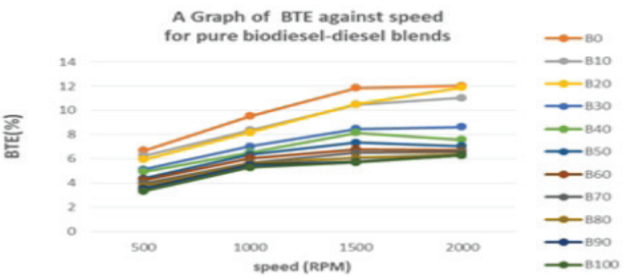


Figure 9. A graph of BTE against speed for pure biodiesel-diesel blends.

Plot of BTE against speed when 5g/l of aluminum oxide was introduced blends

Figure 10 shows plot of BTE against speed when 5g/l of aluminum oxide was introduced in the blends. There was an increase in the brake thermal efficiency when 5g/l of aluminum oxide was introduced. This can be due to reduction in the brake specific fuel consumption of engine which was as a result of the abundance of oxygen in the lattice aluminum oxide. Also, the catalytic nature of aluminum oxide could have caused improved secondary atomization in the combustion chamber. Blends (B0+5g/l, B10+5g/l, B20+5g/l, B30+5g/l, B40+5g/l, B50+5g/l, B60+5g/l, B70+5g/l, B80+5g/l, B90+5g/l, B100+5g/l) had efficiencies 8.2%, 7.5%, 6.75%, 5.6%, 5.5%, 5.1%, 4.9%, 4.5%, 4.3% and 3.7% at low engine speed (500 RPM) and 3.55% and 17.3%, 15.3%, 17.5%, 11.9%, 10.9%, 10.4%, 9.7%, 9.3%, 8.17%, 7.4% and 7.27% at high engine speed (2000 RPM). These results are in line with the works of Shaafi and Velraj, 2015 [41], Sadhik and Anand, 2014 [48], Hosseini et al., 2017 [49] and Khalife, et al., 2017 [57].

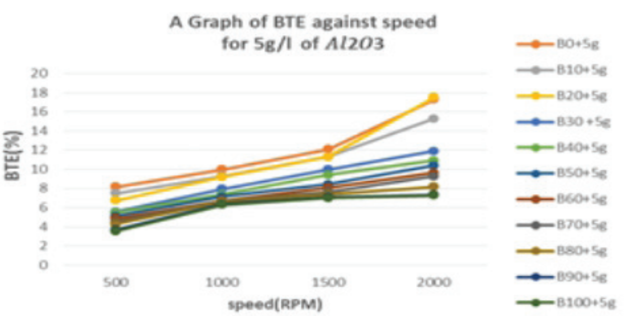


Figure 10. A graph of BTE against speed when 5g/l of aluminum oxide was introduced blends.

Plot of BTE against speed when 10g/l of aluminum oxide was introduced blend

Figure 11 shows plot of BTE against speed when 10g/l of aluminum oxide was introduced in the blends. The introduction of 10g/l of aluminium oxide led to the further increment in the brake thermal efficiency compared to the pure blends, this could be as a result of the secondary atomization offered by aluminium oxide. The secondary atomization leads to an increase in surface area to volume ratio of the fuel, and also the catalytic effect of the nano additive is improved as result of increase in concentration. This eventually led to an increase in the brake thermal efficiency. The blends (B0+10g/l, B10+10g/l, B20+10g/l, B30+10g/l, B40+10g/l, B50+10g/l, B60+10g/l, B70+10g/l, B80+10g/l, B90+10g/l, B100+10g/l) had efficiencies 9.1%, 8.9%, 8.4%, 6.9%, 6.3% 5.8%, 5.6%, 4.9%, 4.2%, 4.0%, 3.9% at low engine speed (500 RPM) and 19.1%, 16.9%, 19.4%, 14.2%, 12.07%, 11.13%, 10.6%, 10.3%, 9.9% at high engine speed (2000 RPM). The findings follow the works of Debbarma and Misra, 2018 [17], Gumus et al., 2015 [26], Gurusala and Selvan, 2015 [31], Arul, et al., 2014 [58] and Attia, et al., 2014 [59].

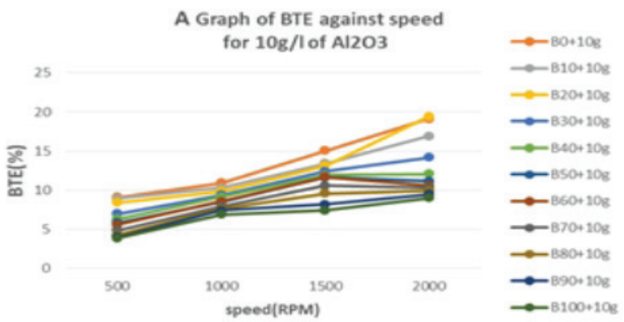


Figure 11. A graph of BTE against speed when 10g/l of aluminum oxide was introduced blend.

Emissions Parameters

Plot of CO against Torque for pure biodiesel-diesel blend

Figure 12 shows the graph of CO emission against torque. Carbon monoxide is an intermediate combustion product and is formed due to insufficient of oxygen and incomplete combustion. The pure diesel fuel has the highest emission of CO, as the volume of the biodiesel in the blends increase the amount of CO emission reduced, this is because the oxygen content of biodiesel is higher than that of diesel. The presence of more oxygen tends to improve the air to fuel ratio in the combustion chamber, this makes the CO emission reduce as the biodiesel content increase in the blends. At low engine torque (25 NM), the emission of the CO is minimal but at higher engine torque (100 NM), the emission of CO is higher this is as a result of reduction in the air to fuel ratio in the combustion chamber. The results corroborate the works of Pandian, 2017 [34], Sadhik and Anand, 2012 [37], Abdel-Razek et al., 2017 [45], Sadhik and Anand, 2014 [48] and Prabu, et al., 2015 [60].

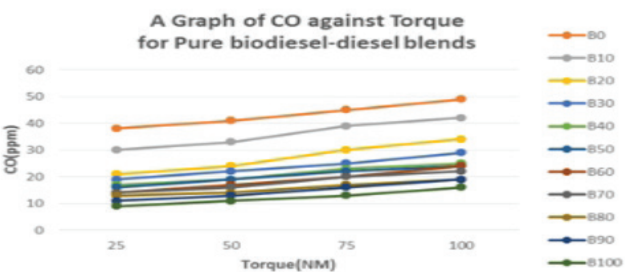


Figure 12. A graph of CO against Torque for pure biodiesel-diesel blend.

CO against Torque when 5g/l of nano additive was introduced into the blends

The graph of CO against torque is shown in the Figure 13. The introduction of aluminum oxide into the blends helps to reduce the emission of CO, this is because the Al_2O_3 introduces more oxygen into the combustion chamber which helps to reduce the incomplete combustion of carbon. At low engine torque (25 NM), the CO emissions of B0, B10, B20, B30, B40, B50, B60, B70, B80, B90, B100 reduced by 5.3% ,6.67%, 14%, 10.5%, 5.9%, 6.25%, 7.1%, 14.3% ,7.7%, 9.1% and 11%. Also, at high engine torque (100 NM), the amount of emissions reduced by 2.04%, 4.8%, 11.76%, 7%, 8%, 4.2%, 8.3%, 9.1%, 5.26%, 10.5% and 6.25%. The results agree favourably with Debbarma and Misra, 2018 [17] and Anand and Sadhik, 2013 [19] and Gumus et al., 2015 [26], Abdel-Razek et al., 2017 [45].

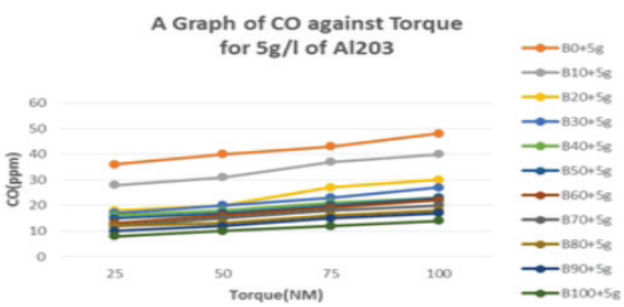


Figure 13. A graph of CO against Torque when 5g/l of nano-additive was introduced into the blends.

Plot of CO against Torque when 10g/l of nano additive was introduced into the blends

The presence of 10g/l of Aluminium oxide as shown in Figure 14, brought about a further reduction in the CO emissions compared to Figure 2-4 because more oxygen was present in the combustion chamber due to increase in the concentration of aluminium oxide. Also the ignition delay was shortened .and there was a further improvement in the air to fuel ratio in the combustion chamber. At low engine torque (25 NM), when 10g/l of aluminium oxide was introduced into the blends B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100 the amount of CO emissions reduced by 10.5%, 13.3%, 28.6%, 21.1% ,11.7%, 12.5%, 14.3%, 21.4% ,15.4%, 18.2% and 22.2%. At high engine torque (100 NM), the amount of CO emissions reduced by 6.1%, 7.14%, 20.6%, 13.8%, 16.0%, 8.33%, 16.7%, 13.6%, 15.8%, 1.9 % and 18.8%. The results are in tandem with that of Sadhik and Anand, 2012 [38], Amit, 2015 [39], Shaafi and Velraj, 2015 [41] and Sadhik and Anand, 2010 [47].

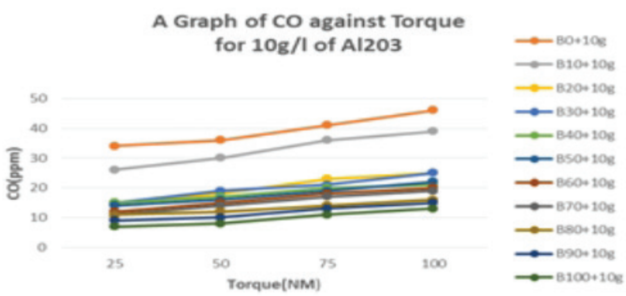


Figure 14. A graph of CO against Torque when 10g/l of nano additive was introduced into the blends.

Plot of NOx against Torque for pure biodiesel-diesel blend

Figure 15 shows graph of NOx against torque. NOx is formed as a result of high temperature in the combustion chamber. The increase in blend ratio leads to an increase in the NOx emissions. This can be as a result of high cetane number of the biodiesel. Also, the increase in NOx emission could be as a result of double bond molecules present in the biodiesel which leads to a higher adiabatic temperature. The high temperature in the chamber could also have been caused as a result of increased engine speed, which enables the nitrogen in the air to form NOx in the combustion chamber. The high cetane number causes an increase in the bonding of the biodiesel, also the double bond molecules in the biodiesel causes a rise in the combustion temperature, this is as a result of the difficulty in the breaking of the double bond. The works of Abdel-Razek et al., 2017

[45], Sadhik and Anand, 2010 [47 and Hosseini et al., 2017 [49] agreed favourably to these results.

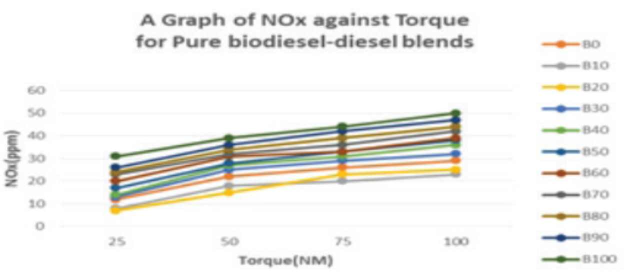


Figure 15. A graph of NOx against Torque for pure biodiesel-diesel blend.

Plot of NOx against Torque when 5g/l of Nano additive was introduced into the blends

Figure 16 shows the graph of NOx against torque. The introduction of Aluminum oxide Nano-additive reduced the NOx emissions in the compression ignition engine. This reduction can be due to the catalytic activity of the Nano-additive, the catalytic activity enables the reaction in the combustion chamber to take place faster, as the reaction in the chamber speeds up, the double bond in the biodiesel takes less time to break. The fuel spent less time in the chamber, this therefore gives room for an unnecessary increase in the combustion temperature in the combustion chamber simply because the rate of reaction is faster. At low engine torque (25 NM), the NOx emissions of B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100 reduced by 16% ,25% ,28.6%, 7.7%, 5.9%, 5.0%, 4.3%, 4.2%, 3.8% and 3.2% and at high engine torque (100 NM), the NOx emission reduced by 3.45%, 8.7%, 16%, 3.1%, 2.78%, 2.6%, 2.5%, 4.76%, 2.3%, 4.3% and 4.0%. The works of Sadhik and Anand, 2010 [36], Sadhik and Anand, 2012 [38], Sadhik and Anand, 2014 [48] and Hosseini et al., 2017 [49] agreed favourably to the results.

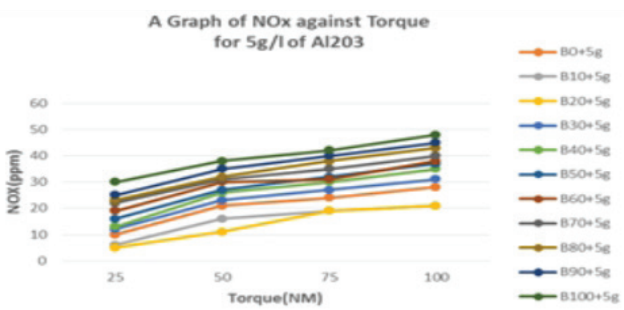


Figure 16. A graph of NOx against Torque when 5g/l of Nano additive was introduced into the blends.

Plot of NOx against Torque when 10g/l of Nano additive was introduced into the blends

Figure 17 shows the graph of NOx against torque. It exhibits a similar characteristic with the 5g/l. The extra 5g/l of aluminum oxide gives room for a further decrease in the amount of NOx produced. At low engine torque (25 NM), the amount of NOx reduced by 25%, 25.1%, 42.9%, 15.4%, 14.3%, 11.7%, 10%, 8.6%, 8.3%, 7.6% and 6.5% for blends of B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100. At high engine torque (100 NM) the amount of NOx reduced by 10.3%, 13%, 32%, 9.4%, 5.6%, 5.3%, 5.13%, 9.52%, 6.82%, 6.4% and 8.0%. These findings agreed favourably with the works of Bet-Moushoul et al.,[16], Debbarma and Misra, [28], Pandian, [35], Sadhik and Anand, [36], Arul Mozhi Selavn, et al., [61], Basne et al [62], Asalekar et al, [63] and Gowda et al,[64].

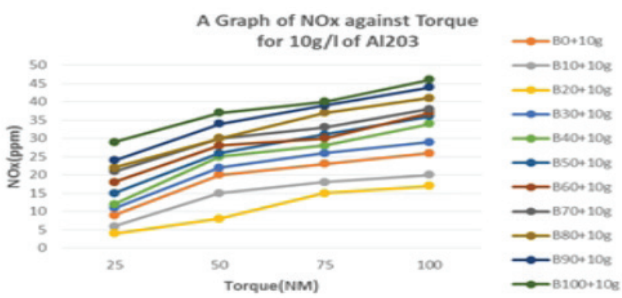


Figure 17. A graph of NOx against Torque when 10g/l of Nano additive was introduced into the blend.

CONCLUSION

This work studied the combinational effects of blends of diesel, waste cooking oil-based biodiesel: B0 to B100 on CI engines; at 10 % incremental step, and aluminum oxide (Al_2O_3) nanoparticles additive with dosages of 5g/l and 10g/l on each fuel blends. From our findings, the following inferences are drawn:

(i) The presence of nano additive in blends of diesel and waste cooking oil-based biodiesel, improves the performance and emission characteristics of compression ignition engine

(ii) The percentage increase of biodiesel in the pure biodiesel-diesel blend at higher engine speeds, gives a decrease in the CO emissions, brake-specific fuel consumption, and an increase in NOx emissions, brake power and brake thermal efficiency

(iii) Blend B20+10g/l gave the best result for performance and emissions characteristics at all investigated speeds and torques, as it increased brake power and BTE by 9.7% and 5% respectively, compared to the pure diesel; and reduced the BSFC by 38%, and CO and NOx emissions by 20.6% and 16% respectively compared to pure diesel.

Thus, in general, it is safe to conclude that, for top performance and emission characteristics of CI engines; pure diesel-waste cooking oil-based biodiesel blend with aluminum oxide nano additive in the proportion of B20 +10 g/l, could be used to fuel compression ignition engines.

Recommendation

It is recommended that the stability of nanofluid based additives through ultrasonic vibration, addition of surfactants and pH control, be investigated. It is further recommended that effect of peak cylinder pressure and heat release rate in CI Engines due to effect of ignition delay and nanofluid based diesel-biodiesel blends calorific values be studied.

NOMENCLATURE

B0	One hundred percent fossil diesel
B0 + 5 g/l	One hundred percent fossil diesel plus 5 g/l of aluminum oxide Nano-additive
B0 + 10 g/l	One hundred percent fossil diesel plus 10 g/l of aluminum oxide Nano-additive
B10	Ten percent biodiesel in diesel-biodiesel blend
B10 + 5 g/l	Ten percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B10 + 10 g/l	Ten percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B20	Twenty percent biodiesel in diesel-biodiesel blend
B20 + 5 g/l	Twenty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B20 + 10 g/l	Twenty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B30	Thirty percent biodiesel in diesel-biodiesel blend
B30 + 5 g/l	Thirty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B30 + 10 g/l	Thirty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B40	Forty percent biodiesel in diesel-biodiesel blend
B40 + 5 g/l	Forty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B40 + 10 g/l	Forty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B50	Fifty percent biodiesel in diesel-biodiesel blend
B50 + 5 g/l	Fifty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B50 + 10 g/l	Fifty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B60	Sixty percent biodiesel in diesel-biodiesel blend
B60 + 5 g/l	Sixty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B60 + 10 g/l	Sixty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B70	Seventy percent biodiesel in diesel-biodiesel blend
B70 + 5 g/l	Seventy percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B70 + 10 g/l	Seventy percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B80	Eighty percent biodiesel in diesel-biodiesel blend
B80 + 5 g/l	Eighty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B80 + 10 g/l	Eighty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B90	Ninety percent biodiesel in diesel-biodiesel blend
B90 + 5 g/l	Ninety percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B90 + 10 g/l	Ninety percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B100	One hundred percent biodiesel
B100 + 5 g/l	One hundred percent biodiesel plus 5 g/l of aluminum oxide Nano-additive
B100 + 10 g/l	One hundred percent biodiesel plus 10 g/l of aluminum oxide Nano-additive
CI	Compression Ignition Engines
CO	Carbon monoxide
NO_X	Nitrogen Oxide
EGT	Exhaust Gas Temperature

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Nabi MN, Hustad JE. Influence of biodiesel addition to Fischer-Tropsch fuel on diesel engine performance and exhaust emissions. Energy Fuels 2010;24:2868-2874. [CrossRef]

[2] Fasogbon SK, Asere AA. Effects of soybean methyl ester on the performance characteristics of compression ignition engine. Int J Mech Mechat Engineer 2014;8:485-488.

[3] Ahmad A, Yasin NM, Derek C, Lim J. Microalgae as a sustainable energy source for biodiesel production: A review. Renew Sustain Energy Rev 2011;15:584-593. [CrossRef]

[4] Carraretto C, Macor A, Mirandola A, Stoppato A, Tonon S. Biodiesel as alternative fuel: Experimental analysis and energetic evaluations. Energy 2004;29:2195-2211. [CrossRef]

[5] Demirbas A. Progress and recent trends in biodiesel fuels. Energy Conver Manage 2009;50:14-34. [CrossRef]

[6] Palash S, Kalam M, Masjuki H, Masum B, Fattah IR, Mofijur M. Impacts of biodiesel combustion on NOx emissions and their reduction approaches. Renew Sustain Energy Rev 2013;23:473-490. [CrossRef]

[7] Mofijur M, Atabani A, Masjuki HA, Kalam M, Masum B. A study on the effects of promising edible and non-edible biodiesel feedstocks on engine performance and emissions production: A comparative evaluation. Renew Sustain Energy Rev 2013; 23:391-404. [CrossRef]

[8] Mofijur M, Masjuki HH, Kalam MA, Atabani AE, Shahabuddin M, Palash SM, et al. Effect of biodiesel from various feedstocks on combustion characteristics, engine durability and materials compatibility: A review. Renew Sustain Energy Rev 2013;28:441-455. [CrossRef]

[9] Kadarohman A, Hernani F, Khoerunisa, Astuti RM. A potential study on clove oil, eugenol and eugenyl acetate as diesel fuel bio-additives and their performance on one cylinder engine. Transport 2010;25:66-76. [CrossRef]

[10] Shaafi T, Velraj R. Influence of alumina nanoparticles, ethanol and isopropanol blend as additive with diesel-soybean biodiesel blend fuel: Combustion, engine performance and emissions. Renewable Energy 2015;80:655-663. [CrossRef]

[11] Aalam CS, Saravanan C. Effects of nano met al oxide blended Mahua biodiesel on CRDI diesel engine. Ain Shams Engineer J 2015;8:689-696. [CrossRef]

[12] Arockiasamy P, Anand RB. Performance, combustion and emission characteristics of a DI diesel engine fuelled with nanoparticle blended jatropha biodiesel. Periodica Polytech Mech Eng 2015;59:88-93. [CrossRef]

[13] Balaji G, Cheralathan M. Effect of CNT as additive with biodiesel on the performance and emission characteristics of a DI diesel engine. Int J ChemTech Res 2015;7:1230-1236.

[14] Basha JS. Impact of carbon nanotubes and di-ethyl ether as additives with biodiesel emulsion fuels in a diesel engine - an experimental investigation. J Energy Inst 2016;91:289-303. [CrossRef]

[15] Bazooyar B, Hosseini SY, Begloo SMG, Shariati A, Hashemabadi SH, Shaahmadi F. Mixed modified Fe2O3-WO3 as new fuel borne catalyst (FBC) for biodiesel fuel. Energy 2018;149:438-453. [CrossRef]

[16] Bet-Moushoul E, Farhadi K, Mansourpanah Y, Nikbakht AM, Molaei R, Forough M. Application of CaO-based/Au nanoparticles as heterogeneous nanocatalysts in biodiesel production. Fuel 2016;164:119-127. [CrossRef]

[17] Debbarma S, Misra RD. Effects of iron nanoparticle fuel additive on the performance and exhaust emissions of a compression ignition engine fueled with diesel and biodiesel. J Therm Sci Engineer Appl 2018;10:041002. [CrossRef]

[18] El-Seesy AI, Hassan H, Ookawara S. Effects of graphene nanoplatelet addition to jatropha biodiesel-diesel mixture on the performance and emission characteristics of a diesel engine. Energy 2018;147:1129-1152. [CrossRef]

[19] Raghuveer D, Vijay M, Sreeraulu D, Suman P, Kumar AS. Production of biodiesel from renewable biological sources. Int'l Conference on Biotechnology, Nanotechnology & Environmental Engineering (ICBNE'15) April 22-23, 2015 Bangkok, Thailand.

[20] Basha JS, Anand RB. The influence of nano additive blended biodiesel fuels on the working characteristics of a diesel engine. J Braz Soc Mech Sci Engineer 2013;35:257-264. [CrossRef]

[21] Avagyan A, Singh B. Biodiesel from Algae. In: Avagyan A, Singh B. Biodiesel: Feedstocks, Technologies, Economics and Barriers. Springer; 2019. [CrossRef]

[22] Keskin A, Gürü M, Altiparmak D. Biodiesel production from tall oil with synthesized Mn and Ni based additives: Effects of the additives on fuel

consumption and emissions. Fuel 2007;86:1139-1143. [CrossRef]

[23] Bhargavi A, Rao BS, Prakash PJ. Performance of Di diesel engine with datura. Int J Mech Product Engineer 2018;6:2320-2322.

[24] Taghizadeh-Alisaraei A, Rezaei-Asl A. The effect of added ethanol to diesel fuel on performance, vibration, combustion and knocking of CI engine. Fuel 2016;185:718e33. [CrossRef]

[25] Shaafi T, Velraj R. Influence of alumina nanoparticles, ethanol and isopropanol blend as additive with dieselesoybean biodiesel blend fuel: Combustion, engine performance and emissions. Renew Energy 2015;80:655e63. [CrossRef]

[26] Gumus S, Ozcan H, Ozbey M, Topaloglu B. Aluminum oxide and copper oxide nanodiesel fuel properties and usage in a compression ignition engine. Fuel 2016;163:80e7. [CrossRef]

[27] Gürü M, Karakaya U, Altıparmak D, Alıcılar A. Improvement of Diesel fuel properties by using additives. Energy Conver Manage 2002;43:1021e5. [CrossRef]

[28] Debbarma S, Misra RD. Effects of iron nanoparticle fuel additive on the performance and exhaust emissions of a compression ignition engine fueled with diesel and biodiesel. J Therm Sci Engineer Appl 2018;10:1-6. [CrossRef]

[29] Rao PPD, Ramarao K, Bharathkumar CH. Characteristics using nano additives in diesel and biodiesel. 2016;5:492-498.

[30] Praveen A, Rao GLN, Balakrishna B. Performance and emission characteristics of a diesel engine using Calophyllum Inophyllum biodiesel blends with TiO2 nanoadditives and EGR. Egypt J Pet 2018;27:731-738. [CrossRef]

[31] Gurusala NK, Selvan VAM. Effects of alumina nanoparticles in waste chicken fat biodiesel on the operating characteristics of a compression ignition engine. Clean Technol Environ Policy 2015;17:681-692. [CrossRef]

[32] Fasogbon SK. Melon oil methyl ester: an environmentally friendly fuel. J Nat Resour Dev 2015;5:47-53. [CrossRef]

[33] Pradipta K, DashaHarish C, DasbShakti P. Investigation on combustion parameters of a producer gas-biodiesel-diethyl ether operated dual fuel engine. Mater Today Proc 2022;62:5928-5933. [CrossRef]

[34] El-Seesy AI, Abdel-Rahman AK, Bady M, Ookawara S. The influence of multi-walled carbon nanotubes additives into non-edible biodiesel-diesel fuel blend on diesel engine performance and emissions. Energ Proc 2016;100:166-172. [CrossRef]

[35] Pandian AK, Ramakrishnan RBB, Devarajan Y. Emission analysis on the effect of nanoparticles on neat biodiesel in unmodified diesel engine. Environ Sci Pollut Res 2017;24:23273-23278. [CrossRef]

[36] Sadhik BJ, Anand RB. Effects of alumina nanoparticles blended Jatropha biodiesel fuel on working characteristics of a diesel engine. Int J Global Warming 2010;2:53-62. [CrossRef]

[37] Sadhik BJ, Anand RB. Performance, emission and combustion characteristics of a diesel engine using Carbon Nanotubes blended Jatropha Methyl Ester Emulsions. Alexandria Engineer J 2014;53:259-273. [CrossRef]

[38] Sadhik BJ, Anand RB. Effects of nanoparticle additive in the water diesel emulsion fuel on the performance, emission and combustion characteristics of a diesel engine. J Vehicle Design 2012;59:164-181. [CrossRef]

[39] Amit SK. Impact on the performance of direct compression ignition engine by adding nano-particle in biodiesel. J Mater Sci Mech Engineer 2015;2:7-9.

[40] Ojeda KA, Herrera AP, Sierra M, Tamayo K. Environmental impact study by life cycle assessment of the use of alumina nanoparticles as an additive in biodiesel/ diesel blends. Chem Eng 2015;17:133-142.

[41] Shaafi T, Velraj R. Influence of alumina nanoparticles, ethanol and isopropanol blend as additive with diesel soybean biodiesel blend fuel: combustion, engine performance and emissions. Renew Energy 2015;80:655-663. [CrossRef]

[42] Hoseini SS, Najafi G, Ghobadian B, Ebadi MT, Mamat R, Yusaf T. Performance and emission characteristics of a CI engine using graphene oxide (GO) nano-particles additives in biodiesel-diesel blends. Renew Energ 2020;145:458-465. [CrossRef]

[43] Junshuai LV, Wang S, Meng B. The effects of nano-additives added to diesel-biodiesel fuel blends on combustion and emission characteristics of diesel engine: A review. Energies 2022;15:1032. [CrossRef]

[44] Devaraj A, Nagappan M, Yogaraj D, Prakash O, Rao YA, Sharma A. Influence of nano-additives on engine behaviour using diesel-biodiesel blend. Matee Today Proc 2022;62:2266-2270. [CrossRef]

[45] Abdel-Razek SM, Gad MS, Omar Thabet OM. Effect of aluminum oxide nano-particle in jatropha biodiesel on performance, emissions and combustion characteristics of DI diesel engine. Int J Res Appl Sci Engineer Technol 2017;5:358-372. [CrossRef]

[46] Rao DS, Dash RK. Investigation on the combustion characteristics of alumina nanoparticles dispersed longer-term stable biodiesel nanofluids. Adv Materials Lett 2016;7:221-225. [CrossRef]

[47] Sadhik BJ, Anand RB. Effects of alumina nanoparticles blended Jatropha biodiesel fuel on working characteristics of a diesel engine. 2010;2:53-62. [CrossRef]

[48] Sadhik BJ, Anand RB. Performance, emission and combustion characteristics of a diesel engine using carbon nanotubes blended jatropha methyl ester emulsions. Alexandria Engineer J 2014;53:259-273. [CrossRef]

[49] Hosseini SH, Taghizadeh-Alisaraei A, Ghobadian B, Abbaszadeh-Mayvan AA. Effect of added alumina as nano-catalyst to diesel-biodiesel blends on performance and emission characteristics of CI engine. Energy 2017;124:543-552. [CrossRef]
[50] Chen AF, Akmal Adzmi M, Adam A, Othman MF, Kamaruzzaman MK, Mrwan AG. Combustion characteristics, engine performances and emissions of a diesel engine using nanoparticle-diesel fuel blends with aluminium oxide, carbon nanotubes and silicon oxide. Energy Conver Manage 2018;171:461-477. [CrossRef]
[51] Devarajan Y, Nagappan B, Subbiah G. A comprehensive study on emission and performance characteristics of a diesel engine fueled with nanoparticle-blended biodiesel. Environ Sci Pollut Res 2019;26:10662-10672. [CrossRef]
[52] D'Silva R, Binu KG, Bhat T. Performance and emission characteristics of a C.I. Engine fuelled with diesel and TiO2 nanoparticles as fuel additive. Mater Today Proc 2015;2:3728-3735. [CrossRef]
[53] EL-Seesy AI, Hassan H, Ookawara S. Performance, combustion, and emission characteristics of a diesel engine fueled with jatropha methyl ester and graphene oxide additives. Energy Conver Manage 2018;166:674-686. [CrossRef]
[54] Ghanbari M, Najafi G, Ghobadian B. Yusaf T, Carlucci AP, Kiani MK. Performance and emission characteristics of a CI engine using nano particles additives in biodiesel-diesel blends and modeling with GP approach. Fuel 2017;202:699-716. [CrossRef]
[55] Gumus S, Ozcan H, Ozbey M, Topaloglu B. Aluminum oxide and copper oxide nanodiesel fuel properties and usage in a compression ignition engine. Fuel 2016:93201613:80-87. [CrossRef]
[56] Hoseini SS, Najafi G, Ghobadian B, Mamat R, Ebadi MT, Yusaf T. Novel environmentally friendly fuel: The effects of nanographene oxide additives on the performance and emission characteristics of diesel engines fuelled with ailanthus altissima biodiesel. Renew Energ 2018;125:283-294. [CrossRef]
[57] Khalife E, Tabatabaei M, Najafi B, Mirsalim SM, Gharehghani A. Mohammadi P, et al. A novel emulsion fuel containing aqueous nano cerium oxide additive in diesel-biodiesel blends to improve diesel engines performance and reduce exhaust emissions: Part I - Experimental analysis. Fuel 2017;207:741-750. [CrossRef]
[58] Selvan VAM, Anand RB, Udayakumar M.. Effect of cerium oxide nanoparticles and carbon nanotubes as fuel-borne additives in diesterol blends on the performance, combustion and emission characteristics of a variable compression ratio engine. Fuel 2014;130:160-167. [CrossRef]
[59] Attia AMA, El-Seesy AI, El-Batsh HM, Shehata MS. Effects of alumina nanoparticles additives into jojoba methyl ester-diesel mixture on diesel engine performance. Energy 2014;6B:V06BT07A019. [CrossRef]
[60] Prabu A, Anand RB. Emission control strategy by adding alumina and cerium oxide nano particle in biodiesel. J Energy Inst 2015:1-7.
[61] Selavn VAM, Anand RB, Udayakumar M. Effect of cerium oxide nanoparticles and carbon nanotubes as fuel-borne additives in diesterol blends on the performance, combustion and emission characteristics of a variable compression ratio engine. Fuel 2014;130:161-167. [CrossRef]
[62] Basne M, Senthilkumar D, Yuvaraj R. Mathematical modelling of evaporation rate and heating of biodiesel blends of a single-component droplets, J Ther Engineer 2023;9:1572–1584. [CrossRef]
[63] Asalekar AJ, Sastry R, Reddy DVA, M. B. S, Barewar SD. Analysis of thermophysical properties of novel hybrid nanoparticles-based vegetable nanofluid, J Ther Engineer 2023;9:1466–1477. [CrossRef]
[64] Gowda BPB, Chandrashekar R, Kumar SM, Akanksh VN. Comparative analysis of carbon particle emissions from exhaust of an IC engine using HSD and blends of HSD and Honge/Jatropha biodiesel. J Ther Engineer 2023;9:1070–1077. [CrossRef]