The influence of propyl gallate antioxidant on the performance and emission characteristics of a diesel engine fueled with blends of *khaya senegalensis* (Mahogany) biodiesel

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Abstract: The objective of this study was to investigate the influence of propyl gallate antioxidant on the performance and emission characteristics of a diesel engine fueled with blends of *khaya senegalensis* (Mahogany) biodiesel on a TD 110-TD 115 single cylinder four-stroke internal combustion diesel engine under constant speed (1500 rpm) and varying load (L1, L2, L3 and L4) conditions coupled with SV 5Q automobile exhaust gas analyser. Khaya senegalensis biodiesel was produced at 6:1 methanol/oil molar ratio, 0.84% wt. catalyst concentration, 70°C temperature and 60 min reaction time. Physicochemical properties of the biodiesel blends were determined using ASTM standard procedures. The fuels used in the analyses are B0, B20, B30 and B100. Propyl gallate antioxidant were added at 1000 ppm concentration to B20, B30 and B100 to study their effect. The results showed that the PG-treated blends decreased the BP by 21.94%, 12.12% and 36.17% as compared to B20, B30 and B100 fuel blends, but increase by 0.99% for B20PG at L4, and increased BSFC by 21.47%, 15.42% and 22.63%. At load L4, the break specific fuel consumption (BSFC) increases for B20PG and B100PG by 12.70% and 1.35%, and reduces for B20PG by 8.09%. Break thermal efficiency (BTE) decreases for B20 and B100 by 28.39%, 18.63% and 34.42%, while B30PG show an increase of 8.02%. Also, B20PG recorded a drop in exhaust gas temperature (EGT) by 15.40%, while B30PG and B100PG had 1.90% and 3.33% increases at a higher load. CO reduces by 0.02% and 0.01% for B30 and B100, CO_2 emission reduces by 2.13%, 2.26% and 15.0%, while, HC emission reduce by 12.73%, 18.18% and 25.45% respectively at engine load L1 and 14.81%, 20.37% and 24.07% at engine load L4 and NOx decreases by B20 (13.85%), B30 (21.54%), B100 (41.54%) compared to that of diesel (B0). However, further research to incorporate the use of this additive in actual automobile applications is recommended to be carry out.
Keywords: khaya senegalensis, propyl gallate, biodiesel, brake power, antioxidant, hydrocarbon

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1 Introduction

Today many countries economic growth rely mainly on the energy (crude oil) as exporter (Ajith et al., 2021). This occurs due to energy considered being the necessary input for industrialization and modernization in improving human welfare, quality of life, economic growth and social development (Sahoo and Das, 2009). Diesel engines are the essential part of industries all around the globe, as they possess excellent characteristics such as high torque, durable and fuel

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economy under wide range of conditions (Özener et al., 2014). Transportation (road and rail), electricity production, civil construction, mining, agriculture and maritime are the major sectors operated with diesel engines (Moron-Villarreyes et al., 2007). Increased world-wide applications resulted in decreased underground carbon resources, climate change and global warming. Diesel engine emit harmful carbon monoxide (CO), hydrocarbon (HC), and oxides of nitrogen (NO_X) emissions (Rosha et al., 2018)

The continuous rise in the total earth's atmospheric temperature is basically attributed to the greenhouse effects occasioned by increased levels of CO_2 and other air pollutants (Ogunkunle and Ahmed, 2020). Greenhouse gases, comprising CO_2, CH_4, and N_2O, are major gaseous emissions that bring about global anthropogenic air pollution (US EPA, 2017). Increasing fossil oil prices, limited reserves of fossil fuels, and environmental concerns have boosted the research on alternative fuel sources such as biodiesels. Moreover, global carbon dioxide (CO_2) emissions from fossil-fuel combustion are increasing every year, intensifying air pollution and magnifying the global warming problems caused by CO_2 (Pereira et al., 2012). The massive utilization of oil and gas derivatives has led to the dramatic exploitation of non-renewable resources, which represents a significant environmental problem that sets an intensified pressure on the energy crisis (Vidal-Daza and Pérez-Vidal, 2018). However, the main concern of both governmental and international organizations is centered on the unprecedented rate of greenhouse emissions derived from convectional energy practices (Alibaba et al., 2020; Espinel-Blanco et al., 2020). Particularly, Internal Combustion Engines (ICEs) represent almost 65% of global CO_2 emissions, given that they are extensively implemented in transportation and energy production (Gutierrez et al., 2020).

Khaya senegalensis (also known as African mahogany or dry-zone mahogany) is a dry zone mahogany plant which is widely found in sub-Saharan Africa. It is valuable for timber, fuelwood and medicinal purposes (Arbonnier, 2004). The growth of African mahogany requires mean annual temperature of 24.5°C – 31.5°C and mean annual rainfall of 400 – 1750 mm. Khaya senegalensis is tolerant to a wide range of soil conditions ranging from neutral to highly acidic and from well drained coarse sandy loam to poorly drained clay. In northern Nigeria, African mahogany is often planted by the road sides to provide shade. The fruit of Khaya Senegalensis is spherical woody capsule (4-6 cm in diameter). Usually, each capsule contains at least six seeds with about 53% by weight oil, does not contain essential fatty acids; hence, it does not have nutritional value and non-edible (Aliyu et al., 2012). However, it is used in traditional medicine of several African communities (Bamaiyi et al., 2006).

Biodiesel fuels have been of great interest in recent years since they have provided both energy and environmental benefits and can be blended with mineral diesel fuel at any proportions (Yesilyurt et al., 2020). Biodiesel is a mixture of fatty acid mono-alkyl esters. It can be produced from wider feedstocks by different methods such as transesterification, micro-emulsion, dilution, and pyrolysis. It has a significant potential for reducing dependence on petroleum-based fossil fuels and is a renewable, environmentally friendly, non-toxic, non-explosive, and free of sulfur fuel. One of the most important properties of biodiesel fuels is lower exhaust emission results (Xue et al., 2011). Biodiesel degrades mainly due to its autoxidation in the presence of atmospheric oxygen. The result of the process of oxidation of biodiesel is the formation of hydroperoxides (ROOH) (Rizwanul Fattah et al., 2014d). Once the hydroperoxides have formed, they are decomposed and then inter-react to form numerous secondary oxidation products, these consist of higher molecular-weight oligomers, often termed polymers (Rizwanul Fattah et al., 2014d). One practical solution to lower the resistance of biodiesels against autoxidation without significantly modifying the fuel properties is to treat them with antioxidants (Fernandes et al., 2013). The main limitation in the use of biodiesel blends is its poor oxidative stability (Dinkov et al., 2009). Biodiesels reacts with oxygen in the atmosphere to produce vaporizable compounds and caustic carboxylic acids which may cause damage to the engine components. To prevent the premature oxidation of unsaturated biodiesel esters, antioxidant is used with biodiesel, keeping them fresh and increasing their shell life (Misra and Murthy, 2011; Kivevele et al., 2011). Studies have shown that by adding antioxidant, the oxidation and NOx levels of biodiesel fuel are considerably reduced (Rashedul et al., 2017; Yuvarajan et al., 2017a, 2017b). CI engine makes use of diesel as fuel for converting the chemical energy into mechanical work. The burning of diesel produces CO, CO_2, HC, NOx, and smoke emissions (Bhave et al., 2022).

Many researchers studied the impact of antioxidants on the performance and emission characteristics of diesel engine fueled with biodiesel blends. Sathiyamoorthi and Sankaranarayanan (2016) studied the effect of addition of two antioxidants Butyl-hydroxyanisol (BHA) and Butyl-hydroxytoluene (BHT) at 2000 ppm with lemongrass oil-diesel blend (LGO25) on engine performance and emission characteristics and concluded that the antioxidant additives exhibited an increase in brake thermal efficiency (BTE) and decrease in exhaust gas temperature (EGT) and specific fuel consumption (BSFC) and reduction of NOx emission. BHA antioxidant additive exhibited a better stability than BHT and provided a maximum NOx reduction of 11% than LGO25 without any antioxidant additives. Balaji and Cheralathan (2015a, 2015b) found that the addition of antioxidant additive (A-tocopherol acetate) in various proportions (100 to 400 ppm) with methyl ester of neem oil was effective in increasing the oxidation stability and reducing the NOx emissions at the expense of slight increases in HC, CO, and smoke emissions. Patel et al. (2019), performed experiments on biodiesels such as *Jatropha*, *Karanja* and *Waste cooking* oil for operating conditions with varying loads and a constant speed of 1500 rpm. *Waste cooking* oil resulted in the increased rate of release of thermal energy as compared to other biodiesels. Reduction in HC and NOx emission was noticed in biodiesels as compared to mineral diesel oil. According to Puhan et al. (2005), the use of *mahua* oil ethyl-ester biodiesel led to an increase in BSFC than when diesel was used. In addition, with a mild increase of 0.22% in BTE, the HC, NOx, Smoke, and CO emissions decreased by 63%, 12%, 70%, and 58%, respectively. While using the animal fat-ethanol blends (Kumar et al., 2006; Kerihuel et al., 2006) and methanol (Kumar et al., 2003) blends of Jatropha biodiesel oil in CI engine under high loading conditions, Kerihuel et al. (2006) reported that the HC, Smoke, and CO emissions decreased significantly compared to when pure fat or diesel was used. Engine combustion, performance, and emission analyses were performed while varying the contents of t-butyl-hydroxyquinone (TBHQ) and propyl gallate (PG). With TBHQ, there was no significant change in smoke, HC, or NOx compared to the untreated fuel. Kivevele et al. (2011), reported that biodiesel dosed with antioxidant PY showed a lower BSF compared to stabilized biodiesel, while having little effect on CO, HC, and NOx emissions. However, at full load condition, stabilized biodiesel showed heat release similar to that of diesel.

The objective of this work is to study the influence of PG antioxidant additives on the performance and emission characteristics of a single-cylinder diesel engine fueled with B20 and B30 Khaya senegalensis biodiesel blend. The antioxidant was used at a concentration of 1000 ppm, which provided high induction periods, improve its oxidation stability and to reduce NOx emission (Alagu et al., 2018), compared to other concentrations.

2 Materials and methods

The crude Khaya senegalensis oil was obtained was obtained from Michika market in Adamawa State, North-eastern Nigeria. All the chemical used, potassium hydroxide, sulfuric acid, isopropyl alcohol and phenolphthalein indicator were of analytical reagent grades. Potassium hydroxide (KOH) in pellet form was used as base catalyst (Danbature et al., 2015). The distilled water needed for washing of biodiesel was provided by local supplier. The conventional and most economical method, two-step transesterification process was adopted for biodiesel production (Rana et al., 2015; Awolu and Layokun, 2013). Khaya senegalensis biodiesel was produced at optimized reaction conditions as reported by Usman (2022). The transesterification reaction was done using reaction variables, viz, 6:1 methanol/oil molar ratio, 0.84% wt catalyst concentration, 70°C temperature and 60 min reaction time. Selected physicochemical properties of the biodiesel were determined using American Society for Testing and Materials (ASTM) standard procedures.

2.1 Acid transesterification of *K. senegalensis* oil

The transesterification was carried out using 50 mL of methanol and 0.2 mL of concentrated H_2SO_4 mixed together inside a 250 mL conical flask. The conical flask was inserted into a water bath at 50°C. The mixture was later added to 200 mL of warmed (preheated) KSO inside a 500 mL round bottom flask and placed on a HS 131 Hotplate Stirrer, continuously stirred, for 1 h for the acid transesterification to take place.

2.2 Alkali transesterification of *K. senegalensis* oil

The pretreated sample oil was heated at 70^0C and 0.84% (w/w) KOH was dissolved in 1:6 molar ratio of methanol to oil in reactor. The reaction was carried out for 60 minutes. After completion of reaction, the mixture was allowed to settle down in separating funnel overnight. A separated layer of methyl ester at top and glycerin layer at the bottom were obtained. Biodiesel thus obtained was washed multiple times with warm distilled water at 50°C until the traces of glycerin were completely washed and it was finally dried with anhydrous $CaCl_2$.

2.3 Preparation of test fuels

Three test fuels were prepared, Khaya senegalensis biodiesel (B100) blended with diesel at 20% by volume (B20), 30% by volume (B30), B20 with PG at concentration of 1000 ppm (B20 + PG), and B30 with PG at concentration of 1000 ppm (B30 + PG) using a magnetic stirrer at 2000 rpm for 30 min.

2.4 Properties of test fuels

For a fuel to be used in a CI engine, the properties of fuel such as viscosity, density, cetane number, volatility and calorific value are of prime importance. Because of the variations of these properties, there is a change in the performance and emission characteristics of the engine (Avase et al., 2015). The properties of diesel, B100, B20 and B30 were measured and compared with ASTM biodiesel standards. Density, kinematic viscosity, iodine value, saponification value, acid value, cloud point, pour point, flash point, free fatty acid, higher heating value and sulphur content. The physiochemical properties of Khaya senegalensis oil and the biodiesel blends were characterized according to ASTM D6751-02 (ASTM, 2002) and standards as described by Onukwuli et al. (2017). The tested properties were found to be having an agreement with ASTM standards. Table 1 shows the properties of fuels.

2.5 Engine test experimental setup

TD 110-TD 115 single cylinder four-stroke internal combustion engine test bed (Figure 1) incorporated with TD114 instrumentation unit (Figure 2) and a TD115 hydraulic dynamometer was used to conduct the engine performance analysis, while measurements of gaseous emissions were carried out with SV 5Q automobile exhaust gas analyser (Figure 3). A schematic of the experimental setup is shown in Figure 4, and the details of the engine and exhaust gas analyser specifications are presented in Table 1 and Table 2 respectively. The engine was connected to dynamometer (TD115 hydraulic dynamometer) for measuring the torque (power output) at varying the loads on the testing engine. The torque transducer, tachometer optical head and exhaust thermocouple were connected to the correct input on the instrumentation unit and calibrated, while the gas analyser probe was connected directly to the exhaust pipe and the insulated line is extended from the exhaust pipe to the equipment units where the analysers are located.

Figure 1 TD 110 – TD 115 Diesel engine test bed

Figure 2 TD114 instrumentation unit

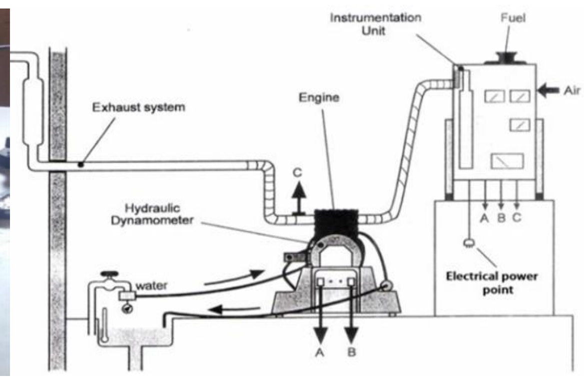

Figure 3 SV-5Q Automobile exhaust gas analyzer

Figure 4 Schematic diagram of TD 110 – TD 115 engine test bed

Table 1 Test engine characteristics/specifications

Parameters	Specifications
Engine Model	TD115
Engine Type	Horizontal single cylinder 4-stroke diesel
Bore × Stroke	85 mm × 85 mm
Brake Power	2.43 kW
Rated Speed	1500 rpm
Starting Method	Manual cranking
Compression Ratio	20.5:1 to 22:1
Net Weight	45 kg
Manufacturer	TQ Educational Training Ltd
Overall dimension	545 mm × 325 mm × 446 mm (L × W × H)
Cooling Method	Air cooling
Number of Cylinder	1
Valve Configuration	OHC 2 valves

Note: Source: (TQ Education and Training: TD110 – TD 115, 2010)

2.6 Engine test procedure

The performance and emission test of blended biodiesel spiked with PG and diesel was carried out on a four-stroke single cylinder direct injection TD 110 – TD 115 engine. Table 1 shows the specifications of the test engine. During testing, no any alteration and modification were made on the test engine. The engine was run with diesel until a steady operating condition was achieved. The engine was operated at constant engine of 1500 rpm and varying load of 500 g-2000 g at 500 g intervals. At each test interval the engine was allowed to run for 10 minutes. After consumption of sufficient blend fuel (8 mL), the data acquisition was started to ensure the removal of residual diesel in the fuel line. After each test, the engine was again run with diesel to drain all of the blend out of the fuel line. This procedure was followed for all blends. The performance and emission measurements were triplicated while, engine exhaust emission concentration (CO, CO_2, HC, oxygen (O_2) and NOx) were measured with an SV-5Q Automobile gas analyser in line with Non-Dispersive Infra-Red (NDIR) technique and recorded.

Table 2 Specifications of SV-5Q Exhaust Gas Analyzer

Measurement range	
HC:	0~10000 10^{-6} (ppm) vol.
CO:	0~10.0 10^{-2} (%) vol.
CO_2:	0~20.0 10^{-2} (%) vol.
O_2:	0~20.0 10^{-2} (%) vol.
NOx:	0~5000 10^{-6} (ppm) vol.
Speed:	0~1000 rpm
Oil temperature	0~120°C
Response Time	
CO, HC, CO_2	≤ 10 s
NO, O_2	≤ 15 s
Power supply:	AC 220+ 10%; 50 Hz + 1 Hz
Gross Weight	15 kg
Packing Size	610 mm × 500 mm× 330 mm

2.7 Determination of brake power (BP)

The engine torque (*T*), measured directly using a Hydraulic dynamometer coupled to the engine output shaft. The power output was calculated from the torque by multiplying by the angular velocity in radians per second using equation (Pulkrabek, 2004).

$$BP = \frac{2\pi NT}{60,000} \quad (1)$$

Where *BP* is brake power (kW), *N* is engine speed (rpm), *T* is torque produced (N m).

2.8 Determination of brake specific fuel consumption (BSFC)

The fuel consumption was determined by measuring the time (*t*) taken for the engine to consume 8 mL of sample fuel as indicated in Figure 2. Thus, the fuel consumption was determined by equation (Chaven and Pathak, 2008).

$$m^{\circ}f = \frac{sgf \times 8 \times 0.001}{t} \times 3600 \quad (2)$$

Where m˚f is fuel consumption (kg hr^{-1}.), sgf is specific gravity of the fuel sample (kg L^{-1}).

Thus, specific fuel consumption was obtained by equation (Jain and Rai, 2010):

$$BSFC = \frac{m^{\circ}f}{BP} \quad (3)$$

Where *BSFC* is brake specific fuel consumption (kg kW^{-1} hr^{-1}).

2.9 Determination of brake thermal efficiency (BTE)

The BTE was determined from the fuel equivalent power (P_{fe}) using equation

$$P_{fe} = \frac{m^{\circ}f \times H_g}{3600} \quad (4)$$

Where, P_{fe} is fuel equivalent power (kW), $m^{\circ}f$ is fuel consumption rate (kg h^{-1}), H_g is higher heatingvalue of the fuel sample (kJ kg^{-1}).

Thus, brake thermal efficiency (*BTE*, %) was obtained by equation 5.

$$BTE = \frac{BP}{P_{fe}} \times 100 \quad (5)$$

3 Results and discussion

3.1 Properties of fuel

The biodiesel prepared in the lab was tested as per ASTM. The standards for different properties with their values are shown in Table 3. It was observed that the main physical properties of ***K. senegalensis*** biodiesel (B20, B30 and B100) were found within acceptable standards for use as an engine fuel. The densities were observed to increase linearly with the increasing concentration of biodiesel in the blends. The density obtained for ***K. senegalensis*** biodiesel is close to the previous work carried out on the same seeds by Danbature et al. (2015) whose result was 871.3 kg m^{-3}. It is clear from the table that kinematic viscosity of the biodiesel blend increases with an increase in biodiesel concentration and vice versa. Higher viscosity results in the power losses, because the high viscosity decreases combustion efficiency due to bad fuel injection atomization (Aydin and Bayindir 2010; Utlu and Koçak, 2008).

Table 3 Properties of fuels

Properties	Unit	KSO	B20	B30	ATSM	EN
Density	Kg m^{-3}	909	851	845	870-900	860-900
Kinematic Viscosity	mm^2 s^{-1}	19.61	4.47	4.51	1.9 - 6.0	3.5 – 5.0
Iodine Value	mgI_2/100g	296.8	127	102	-	120 max
Saponification Value	Mg/KOHg	23	33.66	31.98		
Cloud Point	°C	8.5	12	9.6	-3 – 12	-3 – 10
Pour Point	°C	12	17.5	17	-3 – 16	-15 – 16
Flash Point	°C	295	115	112	130 min	120 max
Acid Value	Mg/KOHg	2.19	0.35	0.65	0.8 max	0.5 max
FFA	%	1.1	0.18	0.33	-	-
HHV	MJ kg^{-1}	44.52	46.15	46.59	45.18	
Sulphur	mg kg^{-1}	0.0476	0.0231	0.0179	-	10 max

3.2 Effect of biodiesel on brake power

The brake power outputs from the engine with different tested fuels and loading conditions are presented in Figure 5. It can be observed that the brake power increased with increasing load and the percentage of biodiesel in the test fuel for B0, B20 and B30, but slightly decrease for B100. The mean brake powers recorded at engine load L1 for B0, B20, B30 and B100 were 0.310, 0.338, 0.330 and 0.235 kW respectively. While the brake power recorded engine load L4 were 1.180, 1.060, 1.218 and 0.707 kW respectively. The higher value for the power at higher load is because more power is generated as the load is being increased. The decrease in BP observed as fuel blends increased could be associated with lower heating value of biodiesel than diesel fuel (Ogunkunle and Ahmed, 2020). Thus, B20 and B30 showed 8.28% and 6.45% more mean brake power, while B100 shows 24.19% less brake power compared to B0 for L1 engine load, while B20 and B100 shows 10.17% and 40.08% less brake power, while B30 shows an increase of 3.22% respectively. However, with the addition of PG antioxidant at 1000 ppm, it resulted in less brake power for B20PG, B30PG and B100PG at load L1 by 21.94%, 12.12% and 36.17% as compared to B20, B30 and B100 fuel blends. While at engine load L4, the brake power decrease for B20PG and B100PG by 11.32% and 0.99%, and 0.99% increase for B20PG respectively. Despite having oxygen content in the molecular structure, B100 produced much lower power output due to having less efficient combustion for its higher kinematic viscosity (Aydin and Bayindir, 2010).

Similar findings were reported by Rizwanul Fattah et al. (2014d).

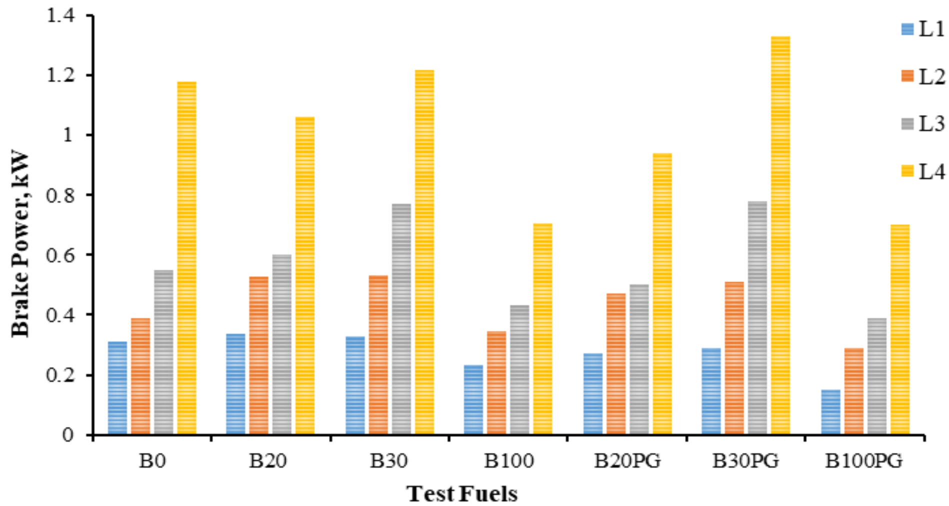

Figure 5 Variation of brake power for test fuels at different engine loads

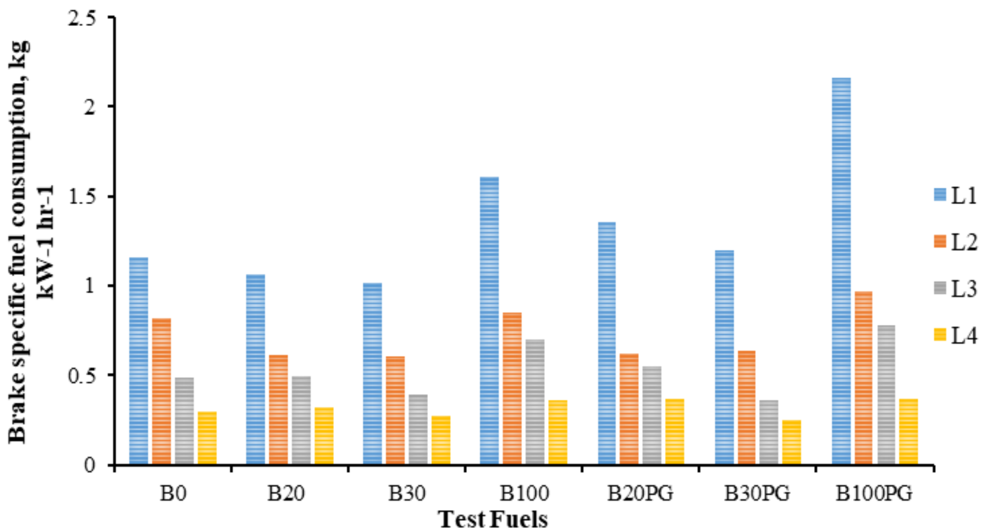

Figure 6 Variation of brake specific fuel consumption for test fuels at different engine loads

3.3 Effect of biodiesel on brake specific fuel consumption

BSFC is defined as the mass of fuel consumed by the engine per unit brake power output. A low value of BSFC is desirable since for a given power less fuel is consumed (Alagu et al., 2018). Figure 6 illustrates the BSFC for all of the test fuels with respect to the engine loads. At L1, more deviation was observed among the test fuel. Increase in the biodiesel concentration shows increase in fuel consumption. However, as the load increases the fuel consumption decreased for all fuel. The decrease in BSFC at L4 load was possibly due to rapid evaporation of water during combustion that provides the higher in-cylinder wall gas temperature and compensates the low energy content by addition of enthalpy (Gopinath and Sundaram, 2015). However, with the addition of PG antioxidant at 1000 ppm, it resulted in BSFC increases for B20PG, B30PG and B100PG at load L1 by 21.47%, 15.42% and 22.63% as compared to B20, B30 and B100 fuel blends. While at load L4, the BSFC show an increase for B20PG and B100PG by 12.70% and 1.35%, and reduction for B20PG by 8.09% respectively. Higher fuel consumption could be attributed to the volumetric effect of the constant fuel injection rate together with the higher viscosity (Rizwanul Fattah et al., 2014d). The reduction in BSFC for B20PG at load L4 may be due to the friction reduction properties of antioxidants which may result in high power output (Alagu et al., 2018). The results agree with studies of Sathiyamoorthi and Sankaranarayanan (2016), Rizwanul Fattah et al. (2014a, 2014b, 2014c).

3.4 Effect of biodiesel on brake thermal efficiency

BTE is defined as the ratio of brake power (BP) to energy in the fuel burned to produce this power. Figure 7 shows the variation of BTE with engine load at constant speed of 1500 rpm. The BTE were found to increase as load increases in every fueling condition. However, the efficiency of the engine decreases (B20 and B100) and increase (B30) as the concentration of biodiesel increases. At load L1, BTE for pure diesel, B20, B30 and B100 were recorded as 6.97%, 7.89%, 7.89% and 5.36% respectively, with the addition of PG antioxidant at 1000 ppm, the BTE decreases by 28.39%, 18.63% and 34.42% respectively for B20, B30 and B100. While at load L4, the BTE for B20 and B100 with PG antioxidant decreases by 15.68% and 8.40%. The lower BTE can be attributed to the combined effect of their lower heating value and higher viscosity (Devan and Mahalakshmi, 2009). The addition of PG antioxidant to B30 show an increase of BTE by 8.02% which can be attributed to the higher power output and lower BSFC compared to B30 (Rizwanul Fattah et al., 2014d). Lower BTE resulted with biodiesel blends are due to the poor volatility and combustion characteristics (incomplete combustion as a result of lack of air content), low calorific, higher density and viscosity value compared to diesel (Ajith et al., 2021). This is in agreement with the study of Yilmaz and Atmanli (2017).

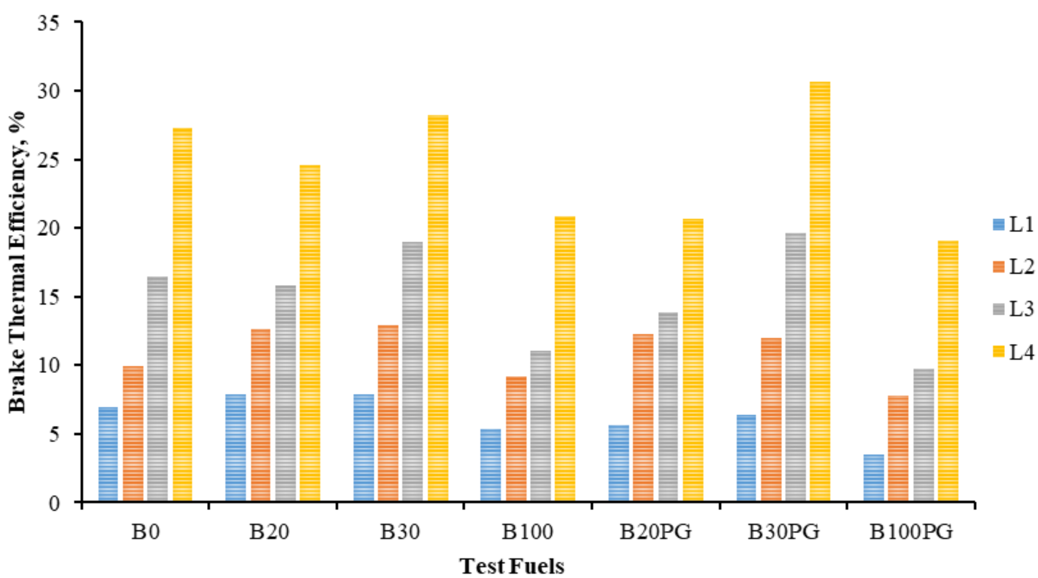

Figure 7 Variation of brake thermal efficiency for test fuels at different engine loads

3.5 Effect of biodiesel on exhaust gas emissions

EGT is one of the substantial factors that influence the exhaust emission characteristics of a CI engine (Yesilyurt et al., 2020). EGT is depended on the fuel properties such as cetane number, kinematic viscosity, density, and calorific value and engine parameters like injection timing and pressure, compression ratio, etc. (Candan et al., 2017). Figure 8 shows how EGT varies with different engine loads that are fueled with blends (B20, B30 and B100) of *K. senegalensis* biodiesel (with addition of PG antioxidant) and pure diesel. It was observed that EGT increases with increase in load, while it decreases with increase in biodiesel concentration in B20, B30 and B100 test fuels as compare to B0. This result agrees with Elshenawy et al. (2019). The higher EGT of B20, B30 and B30 may be attributed to early start of injection and reduction of the premixed combustion phase as a result of shorter ignition delay compared to diesel (Alagu et al., 2018). With the addition of PG antioxidant, at engine load L1, B20PG and B100PG shows an increase in EGT by 3.57% and 7.14% respectively, while B30PG recorded a 9.43% reduction in EGT. Similarly, at engine load L4, B20PG recorded a drop in EGT by 15.40%, while B30PG and B100PG had 1.90% and 3.33% increases in EGT respectively. These results are similar to the study of Rizwanul Fattah et al. (2014d) were Antioxidant-stabilized blends produced mean reductions in EGT of 0.7% – 1% compared to B20.

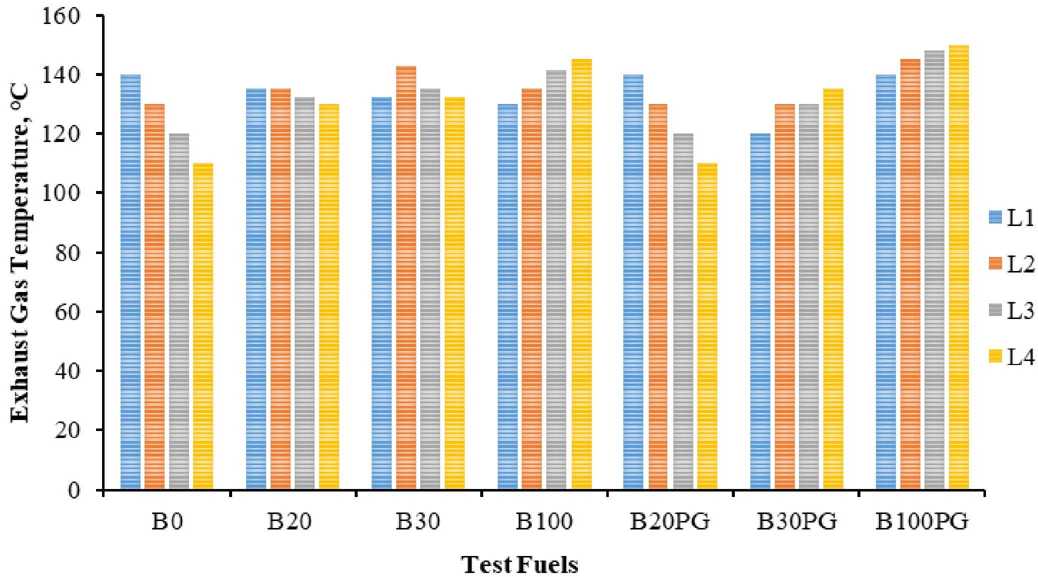

Figure 8 Variation of exhaust gas emissions for test fuels at different engine loads

3.6 Effect of biodiesel on carbon monoxide emissions

Figure 9 presented the Variations of CO emission as a function of engine load with B0, B20, B20PG, B30, B30PG, B100 and B100G biodiesel blends. With all the test fuel compositions, CO emission slightly reduced as loads and biodiesel concentration increased. This illustrates that the emission of CO for diesel is more for all loading conditions than the blended biodiesel. The additional oxygen content in the biodiesel fuel enhances a complete combustion of the fuel, thus reducing CO emissions (Pinto et al., 2005). For B20 and B20PG at engine load L1, the antioxidant shows no significance on the CO emissions, but a 0.01% reduction was observed as load increase. The higher load and rich oxygen mixture result in lower CO emission (Bist and Adhikari, 2021). However, for B30 and B100 at L1, CO emission of 0.14% and 0.15% was recorded respectively, while the addition of PG antioxidant, the emission reduces by 0.02% and 0.01%. At L4, B30 with PG shows no changes in CO emission, while B100PG records 0.025% reductions in CO emission. Increase in biodiesel content increases the oxygen content and lower carbon to hydrogen ratio in the blended fuel as compared to pure diesel (Anbarasu et al., 2018; Bist and Adhikari, 2021). Similar findings was reported by Avase et al. (2015), Bhave et al. (2022), and Busari and Olaoye (2020).

3.7 Effect of biodiesel on carbon dioxide emissions

The CO_2 emission from using conventional diesel (B0), biodiesel (B100, B100PG), and its blends (B20, B20PG, B30, B30PG) are shown on Figure 10. The CO_2 emissions increased with increase in loads and decreased as biodiesel concentrations increased. The increase of CO_2 emission at higher loads was due to higher EGT and lower O_2 concentration in the exhaust, which led to complete combustion (Jafarmadar and Pashae, 2013). The CO_2 emissions for B20, B30 and B100 fuel were found to be 1.41%, 1.33% and 1.20%

lower than diesel (1.88%) fuel, at L1 engine load respectively, whereas with the addition of PG antioxidant to B20, B30 and B100 reduces the CO_2 emission by 2.13%, 2.26% and 15.0% respectively. Similarly, at the engine load L4, the CO_2 emission for B20, B30 and B100 are 1.44%, 1.40% and 1.25% respectively, thus, the addition of PG antioxidant to the biodiesel blends saw a reduction in CO_2 for B30 and B100 by 1.43% and 10.4% respectively. The reduction in CO_2 emission from the engine was due to complete combustion inside the combustion chamber (Mohsin et al., 2014). The lower emissions for biodiesel blends with antioxidants are due to the fact that oxidation stability of biodiesel blend is increased when PG was added, thus lesser tendency of oxygen present in the biodiesel to react with oxygen present in environment (Avase et al., 2015). These results are corroborated by the findings of Ozsezen et al. (2009), Utlu and Koçak (2008), Keskin et al. (2008), and Abed et al. (2019).

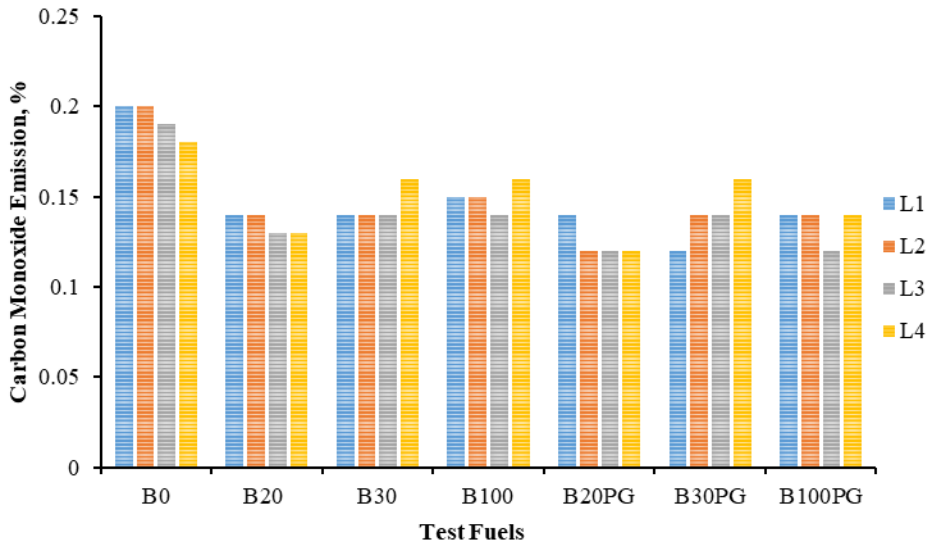

Figure 9 Variation of carbon monoxide emissions for test fuels at different engine loads

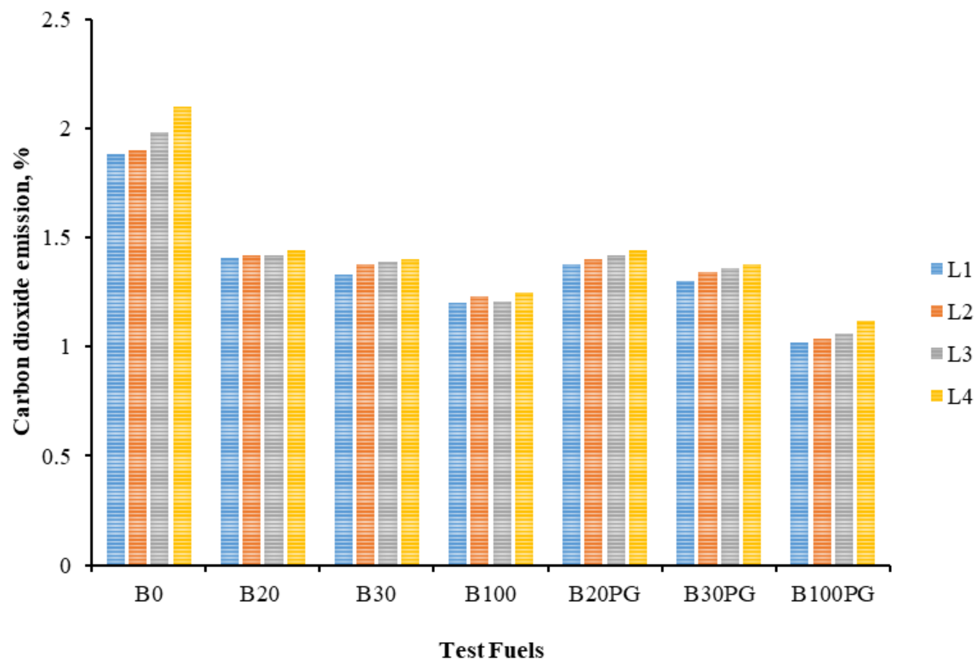

Figure 10 Variation of carbon dioxide emissions for test fuels at different engine loads

3.8 Effect of biodiesel on Hydrocarbon emissions

Figure 11 depict the variation in HC emissions of different biodiesel blends (B20, B30 and B100) without antioxidants and (B20PG, B30PG and B100PG) with antioxidants against different load conditions. It shows that HC emission decreases with increase in loads and biodiesel concentration. In general, the emission of HC depends mainly on the compositions and combustion characteristics of the fuels tested (Tutunea and Dumitru, 2017). Two major causes of HC emissions in diesel engines are: mixing of fuel so that it is leaner than the lean combustion limit during the delay period and under-mixing of fuel, which leaves the fuel injector nozzle late in the combustion process at low velocity (Rizwanul Fattah et al., 2014d). It was observed that at engine load L1, B20, B30 and B100 produce a reduction in HC emission as compared to B0 (diesel) by 11.82%, 16.36% and 25.45% respectively, while a further reduction was observed at engine load L4 by 13.89%, 18.52% and 25% respectively. Increased oxygen content in the test fuel is probably the reason for better combustion and reduction in HC emission (Pinto et al., 2005). However, with the addition of PG antioxidant, B20, B30 and B100 produced a reduction in HC emission by 12.73%, 18.18% and 25.45% respectively at engine load L1 and 14.81%, 20.37% and 24.07% at engine load L4. More heat is generated at higher loads which was responsible for the combustion of the hydrocarbon contents of the blended fuel (Ogunkunle and Ahmed, 2020). It was clear from the findings that the addition of PG antioxidants led to some decreases in HC emission compared to B20, B30 and B100 at all loads, which may be attributed to the fact that their oxidation stability has been increased. The results agreed with Sahoo and Das (2009) who reported a reduction in HC emissions by 20.64%, 20.73% and 6.75% using biodiesel of karanja, jathropa and polanga, Tsolakis et al. (2007) which observed a reduction of nearly 50% for rapeseed biodiesel compared with low sulfur diesel.

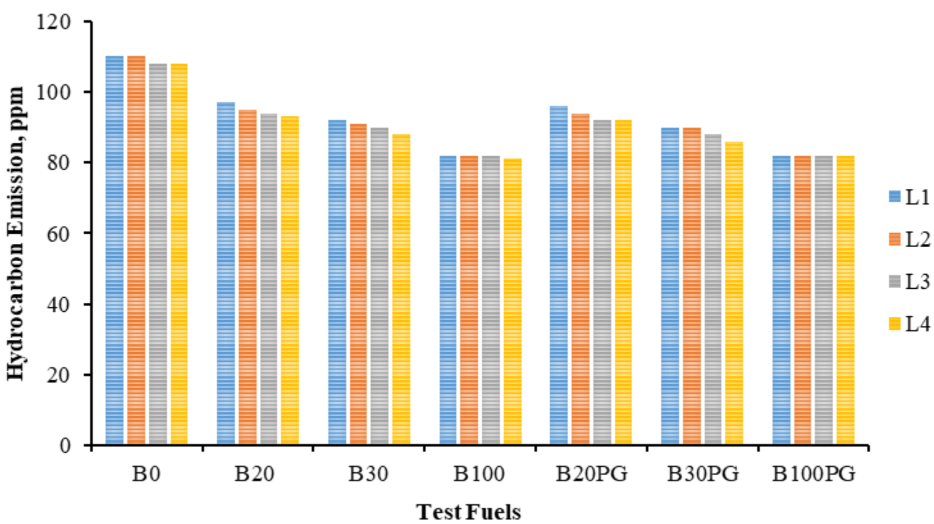

Figure 11 Variation of hydrocarbon emissions for test fuels at different engine loads

3.9 Effect of biodiesel on NOx emissions

Figure 12 indicate the NOx emission variation of different test fuels without and with PG antioxidant. NOx is the most deleterious pollutant that should be controlled at the combustion stage. It is well documented that higher combustion temperature and longer combustion duration inside the combustion chamber, ample local oxygen concentration, and so on are the major factors in NOx formation (Palash et al., 2013). It was generally observed that NOx emission decrease with increase load and biodiesel concentration. The NOx emission values for the biodiesel blends produced a mean decrease of B20 (18.46%), B30 (24.62%), B100 (44.61%) compared to that of diesel

(B0) at engine load L1, while, at engine load L4, the mean reduction in NOx emission values is B20(17.5%), B30(23.33%) and B100(45.0%) respectively. Thus, with the addition of antioxidant, the percentage reduction in the values of NOx decreases from L1 to L4. At engine load L1, the test fuel values of NOx decrease by B20 (13.85%), B30 (21.54%), B100 (41.54%) compared to that of diesel (B0), while for L4 the values are B20 (13.33%), B30 (20.0%) and B100 (40.0%) respectively, compared to that of diesel (B0). These findings agree with literature report of a decrease in NOx emissions when using biodiesel fuels. Dorado et al. (2003) recorded reductions of above 20% from testing biodiesel from waste olive oil in an eight-mode cycle. The formation of NOx depends on cylinder temperature, ignition delay and oxygen content in the fuel, longer chain length and higher amounts of unsaturated fatty acids in methyl ester (Kumar et al., 2014). However, these results are in contrast with the findings of Rizwanul Fattah et al. (2014d), Alagu et al. (2018), and Busari and Olaoye (2020).

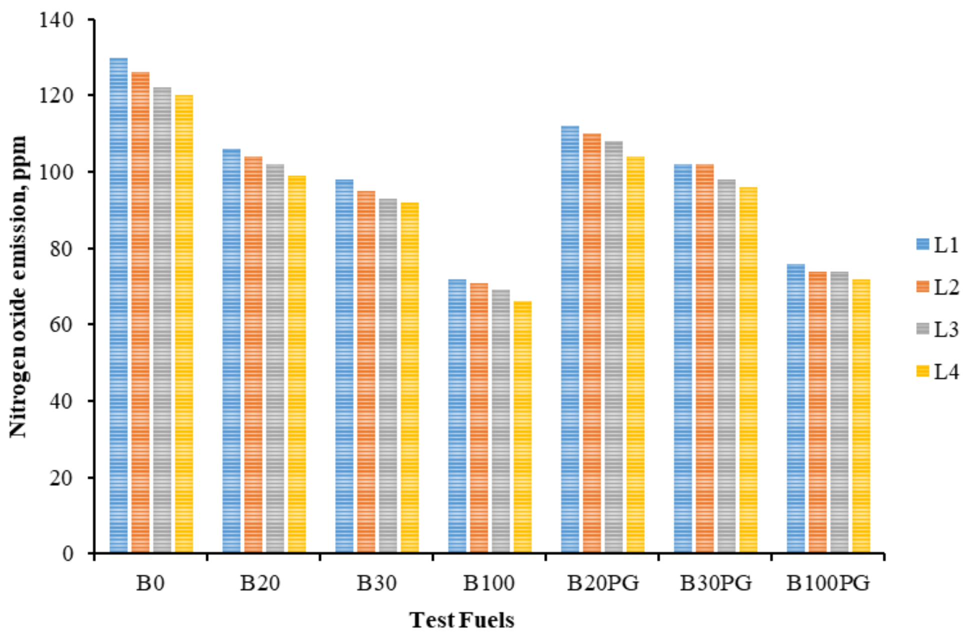

Figure 12 Variation of nitrogen oxide emissions for test fuels at different engine loads

4 Conclusions

The objective of this experimental study was to investigate the impact of PG antioxidant on the performance and emission characteristics of Khaya senegalensis biodiesel blends B20, B30 and B100 on compression ignition engine at different loading conditions. A two-step acid base transesterification process was used to obtain maximum yield. The following findings could be summarized according to the test outcomes:

(1) The finding shows that two-step acid base transesterification was effective in production of biodiesel from Khaya senegalensis seed oil, with the fuel properties conforming to the ASTM D6751 and EN-14214 standards.

(2) The brake power was observed to increase with increasing load and percentage of biodiesel in the test fuel for B0, B20 and B30, but slightly decrease for B100. Thus, B20 and B30 showed 8.28% and 6.45% more mean brake power, while B100 shows 24.19% less brake power compared to B0 for L1 engine load, while B20 and B100 shows 10.17% and 40.08% less brake power, while B30 shows an increase of 3.22% respectively. Addition of PG resulted in less brake power for B20PG (21.94%), B30PG (12.12%) and

B100PG (36.17%) at load L1 and decrease for B20PG (11.32%) and B100PG (0.99%) and B20PG (0.99%) increase respectively as compared to B20, B30 and B100 fuel blends.

(3) Increase in the biodiesel concentration shows increase in BSFC. However, as the load increases the fuel consumption decreased for all fuel. The addition of PG antioxidant at 1000 ppm resulted in BSFC increases for at load L1 by 21.47%, 15.42% and 22.63% as compared to B20, B30 and B100 fuel blends. While at load L4, the BSFC show an increase for B20PG and B100PG by 12.70% and 1.35%, and reduction for B20PG by 8.09% respectively. Higher BSFC could be attributed to the volumetric effect of the constant fuel injection rate together with the higher viscosity.

(4) The BTE were found to increase as load increases in every fueling condition. However, the efficiency of the engine decreases (B20 and B100) and increase (B30) as the concentration of biodiesel increases. With the addition of PG antioxidant at 1000 ppm, the BTE decreases by 28.39%, 18.63% and 34.42% respectively for B20, B30 and B100 at L1. While at load L4, the BTE for B20 and B100 with PG antioxidant decreases by 15.68% and 8.40%. B30PG show an increase of BTE by 8.02% which can be attributed to the higher power output and lower BSFC compared to B30.

(5) At engine load L1, B20PG and B100PG shows an increase in EGT by 3.57% and 7.14%, while B30PG recorded a 9.43% reduction in EGT. Similarly, at engine load L4, B20PG recorded a drop in EGT by 15.40%, while B30PG and B100PG had 1.90% and 3.33% increases in EGT respectively. The higher EGT may be attributed to early start of injection and reduction of the premixed combustion phase as a result of shorter ignition delay compared to diesel.

(5) With all the test fuel compositions, CO emission slightly reduced as loads and biodiesel concentration increased. For B30 and B100 at L1, CO emission of 0.14% and 0.15% was recorded, while the addition of PG, the emission reduces by 0.02% and 0.01%. B30PG shows no changes in CO emission, while B100PG records 0.025% reductions in CO emission. The additional oxygen content in the biodiesel fuel enhances a complete combustion of the fuel, thus reducing CO emissions.

(6) PG antioxidant reduces the CO_2 emission of B20, B30 and B100 at L1 by 2.13%, 2.26% and 15.0% respectively. At L4, reduction in CO_2 emission for B30 and B100 were 1.43% and 10.4% respectively. The reduction in CO_2 emission from the engine was due to complete combustion inside the combustion chamber, while the antioxidant increases the oxidation stability of biodiesel blend.

(7) HC emission decreases with increase in loads and biodiesel concentration. In general, the emission of HC depends mainly on the compositions and combustion characteristics of the fuels tested. With the addition of PG antioxidant, B20, B30 and B100 produced a reduction in HC emission by 12.73%, 18.18% and 25.45% respectively at engine load L1 and 14.81%, 20.37% and 24.07% at engine load L4 as compared to B0 (diesel). Increased oxygen content in the test fuel is probably the reason for better combustion and reduction in HC emission.

(8) NOx emission decrease with increase load and biodiesel concentration. The NOx emission values for the biodiesel blends produced a mean decrease of B20 (18.46%), B30 (24.62%), B100 (44.61%) compared to that of diesel (B0) at engine load L1, while, at engine load L4, the mean reduction in NOx emission values is B20(17.5%), B30(23.33%) and B100(45.0%) respectively. PG addition further decreases NOx emission by B20 (13.85%), B30 (21.54%), B100 (41.54%) compared to that of diesel (B0) at L1 and B20 (13.33%), B30 (20.0%) and B100 (40.0%) respectively, compared to that of diesel (B0) at L4 respectively.

(8) The findings were compared with previous results of other authors from literature. The comparison showed reasonable agreement.

Reference

Abed, K. A., M. S. Gad, A. K. El Morsi, M. M. Sayed, and S. Abu Elyazeed. 2019. Effect of biodiesel fuels on diesel engine emissions. *Egyptian Journal of Petroleum*, 28(2): 183–188.

Ajith, B. S., M. C. Math, G. C. Manjunath Patel, and M. B. Parappagoudar. 2021. Engine performance and exhaust emissions of *Garcinia gummi-gutta* based biodiesel–diesel and ethanol blends. *SN Applied Sciences*, 3: 538.

Alagu, K., B. Nagappan, J. Jayaraman, and A. Arul Gnana Dhas. 2018. Impact of antioxidant additives on the performance and emission characteristics of C.I engine fuelled with B20 blend of rice bran biodiesel. *Environmental Science and Pollution Research*, 25: 17634- 17644.

Alibaba, M., R. Pourdarbani, M. H. K. Manesh, G. V. Ochoa, and J. D. Forero. 2020. Thermodynamic, exergo-economic and exergo-environmental analysis of hybrid geothermal-solar power plant based on ORC cycle using emergy concept. *Heliyon*, 6(4): e03758.

Aliyu, A., E. Lomsahaka, and A. Hamza. 2012. Production of biodiesel via NaOH catalyzed transesterification of mahogany seed oil. *Advances in Applied Science Research*, 3(1): 615-618.

American Society of Testing and Materials (ASTM). 2002. *Annual Book of ASTM for Biodiesel Specification*. Philadephia, PA, USA: ASTM.

Anbarasu, A., V. Muturaman, R. Suthan, and N. Poyyamozhi. 2018. Effect of injection pressure on the performance and emission characteristics of CI engine using canola bio-diesel. *International Journal of Engineering Research and Technology*, 6(2): 1–4.

Arbonnier, M. 2004. Trees, shrubs and lianas of West African dry zones. *Trees, Shrubs and Lianas of West African Dry Zones*, 1-574.

Avase, S. A., S. Srivastava, K. Vishal, H. V. Ashok, and G. Varghese. 2015. Effect of pyrogallol as an antioxidant on the performance and emission characteristics of biodiesel derived from waste cooking oil. *Procedia Earth and Planetary Science*, 11: 437-444.

Awolu, O. O., and S. K. Layokun. 2013. Optimization of two-step transesterification production of biodiesel from neem (*Azadirachta indica*) oil. *International Journal of Energy and Environmental Engineering*, 4: 39.

Aydin, H., and H. Bayindir. 2010. Performance and emission analysis of cottonseed oil methyl ester in a diesel engine. *Renew Energy*, 35(3): 588-592.

Balaji, G., and M. Cheralathan. 2015a. Experimental investigation of antioxidant effect on oxidation stability and emissions in a methyl ester of neem oil fueled DI diesel engine. *Renew Energy*, 74: 910–916.

Balaji, G., and M. Cheralathan. 2015b. Simultaneous reduction of NOx and HC emissions in a CI engine fueled with methyl ester of neem oil using ethylenediamine as antioxidant additive. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 37(24): 2684–2691.

Bamaiyi, L. J., I. S. Ndams, W. A. Toro, and S. Odekina. 2006. Effect of mahogany *Khaya senegalensis* seed oil in the control of *Callosobruchus maculatus* on stored cowpea. *Plant Protection Science*, 42(4): 130–134.

Bhave, N. A., M. M. Gupta, and S. S. Joshi. 2022. Combustion, performance, and emission characteristics of diesel engine using oxyhydrogen gas as a fuel additive. *Environmental Science and Pollution Research*, 30: 24842-24855.

Bist, G. S., and S. P. Adhikari. 2021. Performance and emission characteristics of diesel engine fueled with blends of Neem biodiesel. *Kathmandu University Journal of Science, Engineering and Technology*, 15(3): 1-6.

Busari, R. A., and J. O. Olaoye. 2020. Emission characteristics of a compression ignition engine running castor biodiesel as a blending agent. *CIGR Journal*, 22(2): 112-122.

Candan, F., M. Ciniviz, and İ. Örs. 2017. Effect of cetane improver addition into diesel fuel-methanol mixtures on performance and emissions at different injection pressures. *Thermal Science*, 21(1B): 555–566.

Chaven, D. K., and G. K. Pathak. 2008. *Thermodynamics Engineering*. Delhi, India: Standard Book House, Rajsons Publications PVT. LTD.

Danbature, W. L., J. Aliyu, and H. M. Adamu. 2015. Production of methyl ester from mahogany (*Khaya senegalensis*) seed oil. *Journal of Chemistry and Chemical Sciences*, 5(9): 489-499.

Devan, P. K., and N. V. Mahalakshmi. 2009. Study of the performance, emission and combustion characteristics of a diesel engine using poon oil-based fuels. *Fuel Processing Technology*, 90(4): 513–519.

Dinkov, R., G. Hristov, D. Stratiev, and V. B. Aldayri. 2009 Effect of commercially available antioxidants over biodiesel/diesel blends stability. *Fuel*, 88(4): 732–737.

Dorado, M. P., E. Ballesteros, J. M. Arnal, J. Gómez, and F.

López. 2003. Exhaust emissions from a diesel engine fueled with transesterified waste olive oil. *Fuel*, 82(11): 1311-1315.

Espinel-Blanco, E., G. Valencia Ochoa, and J. Duarte Forero. 2020 Thermodynamic, exergy and environmental impact assessment of S-CO_2 brayton cycle coupled with ORC as bottoming cycle. *Energies*, 13(9): 2259.

Elshenawy, E. A. E., M. A. M. Elkelawy, M. K. El-Fakharany, H. A. Bastawissi, and M. M. Shafey. 2019. Study of the performance and emission characteristics of DI diesel engine fuelled with biodiesel-diesel blends. *International Journal of Advanced Research*, 7(1): 1059-1074.

Fernandes, D. M., R. H. O. Montes, E. S. Almeida, A. N. Nascimento, P. V. Oliveira, E. M. Richter, and R. A. A. Muñoz. 2013. Storage stability and corrosive character of stabilised biodiesel exposed to carbon and galvanised steels. *Fuel*, 107: 609-614.

Gopinath, D., and E. G. Sundaram. 2015. Experimental studies on performance and emission characteristics of diesel engine fuelled with neem oil methyl ester blends. *International Energy Journal*, 15(1): 33–42.

Gutierrez, J. C., G. Valencia Ochoa, and J. Duarte-Forero. 2020. Regenerative organic rankine cycle as bottoming cycle of an industrial gas engine: traditional and advanced exergetic analysis. *Applied Sciences*, 10(13): 4411.

Jain, S. C., and C. R. Rai. 2010. *Farm Tractors*. 2nd ed. Delhi, India: Standard Publisher Distributors.

Jafarmadar, S., and J. Pashae. 2013. Experimental study of the effect of castor oil biodiesel fuel on performance and emissions turbocharged DI diesel. *International Journal of Engineering-Transactions B: Applications*, 26(8): 905-912.

Kerihuel, A., M. S. Kumar, J. Bellettre, and M. Tazerout. 2006. Ethanol animal fat emulsions as a diesel engine fuel– Part 1: Formulations and influential parameters. *Fuel*, 85(17-18): 2640-2645.

Keskin, A., M. Gürü, and D. Altıparmak. 2008. Influence of tall oil biodiesel with Mg and Mo based fuel additives on diesel engine performance and emission. *Bioresource Technology*, 99(14): 6434–6438.

Kivevele, T. T., L. Kristóf, Á. Bereczky, and M. M. Mbarawa. 2011. Engine performance, exhaust emissions and combustion characteristics of a CI engine fuelled with croton *megalocarpus* methyl ester with antioxidant. *Fuel*, 90(8): 2782-2789.

Kumar, P., M. P. Sharma, and G. Dwivedi. 2014. Impact of biodiesel on combustion, performance and exhaust emissions of diesel engines. *Journal of Integrated Science and Technology*, 2(2): 57–63.

Kumar, M. S., A. Kerihuel, J. Bellettre, and M. Tazerout. 2006. Ethanol animal fat emulsions as a diesel engine fuel– Part 2: Engine test analysis. *Fuel*, 85(17-18): 2646-2652.

Kumar, M. S., A. Ramesh, and B. Nagalingam. 2003. An experimental comparison of methods to use methanol and Jatropha oil in a compression ignition engine. *Biomass and Bioenergy*, 25(3): 309-318.

Misra, R. D., and M. S. Murthy. 2011. Blending of additives with biodiesels to improve the cold flow properties, combustion and emission performance in a compression ignition engine—A review. *Renewable and Sustainable Energy Reviews*, 15(5): 2413–2422.

Mohsin, R., Z. A. Majid, A. H. Shihnan, N. S. Nasri, and Z. Sharer. 2014. Effect of biodiesel blends on engine performance and exhaust emission for diesel dual fuel engine. *Energy Conversion and Management*, 88: 821-828.

Moron-Villarreyes, J. A., C. Soldi, A. M. de Amorim, M. G. Pizzolatti, A. P. de Mendonça Jr., and M. G. M. D'Oca. 2007. Diesel/biodiesel proportion for by-compression ignition engines. *Fuel*, 86(12-13): 1977-1982.

Onukwuli, D. O., L. N. Emembolu, C. N. Ude, S. O. Aliozo, and M. C. Menkiti. 2017. Optimization of biodiesel production from refined cotton seed oil and its characterization. *Egyptian Journal of Petroleum*, 26(1): 103–110.

Ogunkunle, O., and N. A. Ahmed. 2020. Exhaust emissions and engine performance analysis of a marine diesel engine fueled with *Parinari polyandra* biodiesel–diesel blends. *Energy Reports*, 6: 2999–3007.

Ozsezen, A. N., M. Canakci, A. Turkcan, and C. Sayin. 2009. Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. *Fuel*, 88(4): 629–636.

Özener, O., L. Yüksek, A. T. Ergenç, and M. Özkan. 2014. Effects of soybean biodiesel on a DI diesel engine performance, emission and combustion characteristics. *Fuel*, 115: 875–883.

Patel, C., K. Chandra, J. Hwang, R. A. Agarwal, N. Gupta, C. Bae, T. Gupta, and A. K. Agarwal. 2019. Comparative compression ignition engine performance, combustion, and emission characteristics, and trace metals in particulates from Waste cooking oil, Jatropha and Karanja oil derived biodiesels. *Fuel*, 236: 1366– 1376.

Palash, S. M., M. A. Kalam, H. H. Masjuki, B. M. Masum, I. M. Rizwanul Fattah, and M. Mofijur. 2013. Impacts of biodiesel combustion on NOx emissions and their reduction approaches. *Renewable and Sustainable Energy Reviews*, 23: 473–490.

Pereira, R. G., O. E. P. Tulcan, C. E. Fellows, V. de Jesus Lameira, O. L. G. Quelhas, M. E. de Aguiar, and D. M. do Espirito Santo Filho. 2012. Sustainability and mitigation of greenhouse gases using ethyl beef tallow biodiesel in energy generation. *Journal of Cleaner Production*, 29-30: 269-276.

Pinto, A. C., L. L. N. Guarieiro, M. J. C. Rezende, N. M. Ribeiro, E. A. Torres, W. A. Lopes, P. A. P. Pereira, and J. B. de Andrade. 2005. Biodiesel: An overview. *Journal of the Brazilian Chemical Society*, 16(6): 1313-1330.

Pulkrabek, W. W. 2004. *Engineering Fundamentals of the Internal Combustion Engine*. 2nd ed. Upper Saddle River, NJ, USA: Pearson Prentice Hall.

Puhan, S., N. Vedaraman, B. V. B. Ram, G. Sankarnarayanan, and K. Jeychandran. 2005. Mahua oil (*Madhuca Indica* seed oil) methyl ester as biodiesel-preparation and emission characterstics. *Biomass Bioenergy*, 28(1): 87–93.

Rana, S. M. S., M. A. Haque, S. Poddar, S. M. A. Sujan, M. Hossain, and M. S. Jamal. 2015. Biodiesel production from non-edible Mahogany seed oil by dual step process and study of its oxidation stability. *Bangladesh Journal of Scientific and Industrial Research*, 50(2): 77-86.

Rashedul, H. K., M. A. Kalam, H. H. Masjuki, Y. H. Teoh, H. G. How, I. M. Monirul, and H. K. Imdadul. 2017. Attempts to minimize nitrogen oxide emission from diesel engine by using antioxidant-treated diesel-biodiesel blend. *Environmental Science and Pollution Research*, 24: 9305–9313.

Rizwanul Fattah, I. M., H. H. Masjuki, M. A. Kalam, M. A. Hazrat, B. M. Masum, S. Imtenan, and A. M. Ashraful. 2014d. Effect of antioxidants on oxidation stability of biodiesel derived from vegetable and animal-based feedstocks. *Renewable and Sustainable Energy Reviews*, 30: 356-370.

Rizwanul Fattah, I. M., H. H. Masjuki, M. A. Kalam, M. Mofijur, and M. J. Abedin. 2014a. Effect of antioxidant on the performance and emission characteristics of a diesel engine fueled with palm biodiesel blends. *Energy Conversion and Management*, 79: 265–272.

Rizwanul Fattah, I. M., H. H. Masjuki, M. A. Kalam, M. A. Wakil, A. M. Ashraful, and S. A. Shahir. 2014b. Experimental investigation of performance and regulated emissions of a diesel engine with *Calophyllum inophyllum* biodiesel blends accompanied by oxidation inhibitors. *Energy Conversion and Management*, 83: 232–240.

Rizwanul Fattah, I. M., H. H. Masjuki, M. A. Kalam, M. A. Wakil, H. K. Rashedul, and M. J. Abedin. 2014c. Performance and emission characteristics of a CI engine fueled with *Cocos nucifera* and *Jatropha curcas* B20 blends accompanying antioxidants. *Industrial Crops and Products*, 57: 132–140.

Rosha, P., A. Dhir, and S. K. Mohapatra. 2018. Influence of gaseous fuel induction on the various engine characteristics of a dual fuel compression ignition engine: a review. *Renewable and Sustainable Energy Reviews*, 82(Part 3): 3333-3349.

Sathiyamoorthi, R., and G. Sankaranarayanan. 2016. Effect of antioxidant additives on the performance and emission characteristics of a DICI engine using neat lemongrass oil–diesel blend. *Fuel*, 174: 89–96.

Sahoo, P. K., and L. M. Das. 2009. Process optimization for biodiesel production from Jatropha, Karanja and Polanga oils. *Fuel*, 88(9): 1588–1594.

Tsolakis A, A. Megaritis, M. L. Wyszynski, and K. Theinnoi. 2007. Engine performance and emissions of a diesel engine operating on diesel-RME (rapeseed methyl ester) blends with EGR (exhaust gas recirculation). *Energy*, 32(11): 2072-2080.

Tutunea, D., and I. Dumitru. 2017. Analysis of performance and emissions of diesel engine using sunflower biodiesel. *IOP Conf erence Series: Materials Science and Engineering*, 252: 012085.

Utlu, Z., and M. S. Koçak. 2008. The effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions. *Renewable Energy*, 33(8): 1936-1941.

US EPA. 2017. Greenhouse Gas Emissions: Overview of Greenhouse Gases. Washington, DC, USA: US Environmental Protection Agency.

Usman D. D**.**, O. U. Dairo, O. J. Adeosun and B. G. Jahun (2022) Physicochemical properties of biodiesel blends derived from mahogany (*Khaya senegalensis*) seed oil for use as alternative fuel. *Journal of Agricultural Engineering and Technology (JAET)*, 27 (1); 28 - 43.

Vidal-Daza, O. A., and A. Pérez-Vidal. 2018. Estimation of dilution of atmospheric contaminants from a paper factory using the AERMOD model. *Ingeniería*, 23(1): 31-47.

Xue, J., T. E. Grift, and A. C. Hansen. 2011. Effect of biodiesel on engine performances and emissions. *Renewable and Sustainable Energy Reviews*, 15(2): 1098-1116.

Yesilyurt, M. K., Z. Yilbasi, and M. Aydin. 2020. The performance, emissions, and combustion characteristics of an unmodified diesel engine running on the ternary blends of pentanol/safflower oil biodiesel/diesel fuel. *Journal of Thermal Analysis and Calorimetry*, 140: 2903–2942.

Yilmaz, N., and A. Atmanli. 2017. Experimental assessment of a diesel engine fueled with diesel-biodiesel-1-pentanol blends. *Fuel*, 191: 190–197.

Yuvarajan, D., M. Dinesh Babu, N. BeemKumar, and P. Amith Kishore. 2017a. Experimental investigation on the influence of titanium dioxide nanofluid on emission pattern of biodiesel in a diesel engine. *Atmospheric Pollution Research*, 9(1): 47-52.

Yuvarajan, D., D. B. Munuswamy, A. Mahalingam, and B. Nagappan. 2017b. Performance, combustion and emission analysis of neat palm oil bio-diesel and higher alcohol blends in diesel engine. *Energy & Fuels*, 31(12): 13796-13801.