

2016

Impact of Antioxidant Additives on the Engine Performance and Exhaust Emissions Using Biodiesel made from Jatropha Oil of Eastern Africa Origin

Kivevele, Thomas

Journal of the South African Institution of Mechanical Engineering

<https://dspace.nm-aist.ac.tz/handle/20.500.12479/833>

Provided with love from The Nelson Mandela African Institution of Science and Technology

Impact of Antioxidant Additives on the Engine Performance and Exhaust Emissions Using Biodiesel made from Jatropha Oil of Eastern Africa Origin

T Kivevele^{a,b}, Z Huan^a, L Kristóf^c, Á Bereczky^c, M Mbarawa^d

Received 23 March 2015, in revised form 17 June 2015 and accepted 7 April 2016

Biodiesel's chemical nature makes it more susceptible to oxidation in comparison to mineral diesel. Biodiesels are doped with antioxidants to increase oxidation stability for long term storage. However, it is quite possible that these additives may affect fuel related properties of biodiesel such as cetane number and kinematic viscosity and also the performance of engine and exhaust emissions. Therefore, this study investigated the effects of antioxidant on the oxidation stability, cetane number and kinetic viscosity of biodiesel made from jatropha oil of Eastern Africa origin. Also, the influence on the performance and exhaust emissions of a four cylinder turbocharged direct injection (TDI) diesel engine. Antioxidant 1, 2, 3 tri-hydroxy benzene (Pyrogallol, PY), as the most effective antioxidant based on the earlier work of the authors was mixed with the produced Jatropha Oil Methyl Ester (JOME) at different concentrations to improve the oxidation stability. The results showed that, the oxidation stability of JOME increased with the increase of PY dosage. Also, cetane number slightly increased with additional of antioxidant whereas kinetic viscosity was observed to decrease with PY dosage. The brake specific fuel consumption (BSFC) of JOME with antioxidants decreased more than that without antioxidants, but both were higher than that of diesel and diesel/biodiesel blends. No significant effects were observed on the exhaust emissions of a diesel engine running on biodiesel (JOME) dosed with antioxidant PY.

Additional keywords: Jatropha oil, antioxidants, fuel properties, engine performance, emissions

1 Introduction

Increasing prices of fossil fuels and environmental concern have increased the search for alternative fuel sources^{1,2}. Apparently, biodiesel is emerging as potential alternative

fuel to replace petroleum-based diesel^{1,3}. Biodiesel is derived from vegetable oil, animal fat or waste cooking oil and can be used directly in CI engines or blended with petro-diesel at any percentage without engine modification⁴. Biodiesel possesses significant technical advantages over petro-diesel, such as derivation from a renewable and domestic feedstock, inherent lubricity, essentially no sulfur content, superior flash point and biodegradability, as well as reductions in most exhaust emissions^{3,4}. Despite the advantages of biodiesel over mineral diesel, its chemical nature makes it more susceptible to oxidation in comparison to petro-diesel. Thus, biodiesels are doped with antioxidants to increase oxidation stability for long term storage. However, it is quite possible that these additives may affect other basic fuel related properties of biodiesel such as cetane number and kinematic viscosity and also possible it can influence the engine performance and exhaust emissions⁵.

There limited studies in the open literature that investigated the influence of antioxidants on the performance, exhaust emissions and combustion characteristics of diesel engines running on biodiesel with antioxidants. Ryu^{6,7} studied the effect of antioxidants on the oxidation stability, performance and exhaust emissions from a diesel engine fuelled with soybean based biodiesel and the results of exhaust emissions were compared with diesel. Biodiesel was dosed with antioxidants, tert-butylhydroquinone (TBHQ) and 3, 4, 5-tri hydroxy benzoic acid (Propyl Gallate, PG) in the concentration of 0, 300, 500, 1000 and 2000 ppm. The results indicated that, at lower loads, the hydrocarbons (HC), nitrogen oxide (NOx) and smoke were comparable with diesel while at higher loads; HC and smoke were very high with diesel fuel compared to biodiesel with or without antioxidants. NOx emissions with diesel were lower than biodiesel with or without antioxidants. No appreciable difference was observed in NOx emission with neat biodiesel and biodiesel dosed with antioxidants. It was inferred that the antioxidants which are responsible for stabilizing the biodiesel for longer time, when applied to practical conditions, have no noticeable negative effect of exhaust emissions. Also, it was reported that, the brake specific fuel consumption (BSFC) of biodiesel with or without antioxidant was observed to be higher compared to diesel at all loads. However, comparing biodiesel with and without antioxidant, the BSFC of biodiesel with antioxidant was lower than untreated biodiesel. Similar observations on the influence of antioxidant additives on the performance, exhaust emissions and combustions characteristics of diesel engine running on biodiesel dosed with antioxidants were reported elsewhere

- Department of Mechanical Engineering, Mechatronics and Industrial Design, Tshwane University of Technology, Private Bag X680, Pretoria 0001, South Africa (kivevelethomas@gmail.com)
- Department of Energy and Production Engineering, Mbeya University of Science and Technology, P. O. Box 131, Mbeya-Tanzania.
- Department of Energy Engineering, Budapest University of Technology and Economics, Muegyetem rkp. 3-9. H-1111 Budapest, Hungary.
- Ministry of Works, Transport and Communication, Tancot House, 2 Pamba Street, P. O. Box 9144, 11476 Dar es Salaam - Tanzania.

in the literature for edible and non-edible feedstocks; canola^{8,9}, palm¹⁰ and croton *megalocarpus* oil⁴. From these few lines it can be seen that, most of the studies investigated the influence of antioxidant additives on the performance and exhaust emissions of diesel engines using biodiesel made from edible oils than from non-edible oils such as jatropha oil which do not pose threat on food availability. Also, the impact of antioxidant additives on other basic fuel related properties such as cetane number and kinematic viscosity of biodiesels were not clearly reported.

The use of edible vegetable oil for biodiesel production has not been successful because of its unstable price and due to food versus fuel conflict¹¹. As the demand for vegetable oils for food has increased substantially in recent years, it would be better to use non-edible oils for biodiesel production¹². Therefore, non-edible oils, such as jatropha oil, will become significant sources for biodiesel production now or in the future¹¹. Jatropha is a fast growing plant, which requires little water or fertilizer; it can survive in infertile soils¹². Jatropha oil is mostly found in developing countries especially Africa and Asia. Jatropha plants have a high seed yield which can be continuously produced for 30 – 40 years. The oil content in the jatropha seeds is approximately 30 – 40 % by weight^{12,13}. The problem with jatropha oil is the high free fatty acids (FFA) content of approximately 14 %¹⁴ which requires two steps of biodiesel production (esterification followed by transesterification process). Also another concern with biodiesel derived from jatropha oil is rich in unsaturated fatty acid methyl esters^{5,14} which are prone to oxidation and requires antioxidant additives for longer storage.

Therefore, in this study, production of biodiesel from jatropha oil (Jatropha Oil Methyl Ester - JOME) and determination of its fuel related properties were carried out. Investigation of oxidation stability without and with antioxidant using Rancimat instrument was also conducted, as recommended in European biodiesel standard (EN 14112). Also, the influence of antioxidant additive on the kinetic viscosity and cetane number of JOME was conducted. Additionally, experimental investigation on the effect of antioxidant on the engine performance and exhaust emissions was performed using JOME without and with 1000 ppm of an antioxidant PY and the results were compared with that of B20 and mineral diesel.

2 Materials and Methods

2.1 Materials

Jatropha oil was purchased from Diligent Tanzania Limited (Arusha-Tanzania), mineral diesel from a local filling station in Budapest, Hungary which was used for comparison purposes and for making blends with jatropha biodiesel. The antioxidants: 1, 2, 3 tri-hydroxy benzene (Pyrogallol – PY, purity grade > 98 %) was from Alfa Aesar Company, Germany. The chemicals used in this study were analytical reagents: potassium hydroxide, 85 % and methanol, 99.5 %, which were obtained from the chemistry laboratory (Arcadia campus), Tshwane University of Technology, Pretoria, South Africa.

2.2 Biodiesel production

Jatropha oil had high FFA contents of 10.5 % which was above 2 % required to produce biodiesel using two steps. The first step was the esterification process in the presence of catalyst (0.5 % H₂SO₄, w/w oil) and 6:1 methanol/oil molar ratio^{14,15} followed by the step of transesterification process which was performed at the following standard conditions: 6:1 methanol/oil molar ratio, 1.0 wt % potassium hydroxide, 60 °C reaction temperature, 400 rpm agitation speed, and 90 min reaction time. The measured amount of jatropha oil was dehydrated by heating to 110 °C and allowed to cool to room temperature. The amount of oil was weighed and placed in a beaker equipped with a magnetic stirrer and thermometer. The oil was then heated under agitation to the desired temperature on a heating plate. The amount of catalyst (KOH) was poured into a beaker containing a measured amount of methanol and allowed to mix for a while at room temperature. After the oil temperature reached the desired point, the prepared catalyst-methanol solution was added to the oil, taking this moment as the starting time of the reaction; thereafter, the mixture was stirred for 90 min at 60 °C. After completion of the reaction process, the mixture was transferred to a separating funnel and allowed to cool to room temperature without agitation, leading to the separation of two distinct phases. The upper phase consisted primarily of JOME, while the lower phase contained glycerol, excess methanol and catalyst, soap formed during the reaction, some entrained JOME, and partial glycerides. The upper phase, i.e., methyl ester (biodiesel), was washed with deionized water at 50 °C repeatedly until the washing water became clear, to remove traces of glycerine, unreacted catalyst, and soap formed during the transesterification process. The ester was then subjected to heating at 110 °C to remove excess alcohol and water. The final product (biodiesel) formed as a clear, light yellow liquid.

2.3 Property determination

The produced JOME was tested for physical and chemical fuel related properties and were compared to mineral diesel and the global biodiesel standards such as American Society for Testing and Materials (ASTM) D6751 and European biodiesel standards (EN14214). Kinematic viscosity with and without antioxidant additives was determined using the miniature U-tube and viscometer model: TV 4000 as per ASTM D445. The cloud point (CP), pour point (PP) and the cold filter plugging point (CFPP) were determined as per ASTM D2500, D97 and D6371 respectively. The cetane number of the samples with and without antioxidant additives was determined as per ASTM D613 using a CFR (Waukesha F-5) engine. The calorific value of JOME was determined using a bomb calorimeter as prescribed in ASTM D240. A density meter model: DA-130N was used to determine the density of JOME as per ASTM D941. The acid value was determined as per ASTM D974. Pensky Marten's flash point tester (Stanhope-SETA: 34000 – 0 U) was used to determine flash point of JOME as per ASTM D93. The lubricity in the present study was determined using a high-frequency reciprocating ring (HFRR) as prescribed in ISO 1256 HFRR test method. Oxidation

stability without and with different dosages of antioxidant additive was studied using a Rancimat instrument (Make: Metrohm, Switzerland; Model: 873) as prescribed in EN 14112¹⁶.

The fatty acid composition of biodiesel was analysed by using a Gas Chromatography Mass Spectroscopy (GC MS) (Agilent 6890N); GC was coupled to an inert mass-selective detector (MSD) (Agilent 5973). A 1 µL biodiesel sample was injected using a split ratio of 200:1 in an auto sampler at 24.79 psi at an inlet temperature of 250 °C. The GC was equipped with a polyethylene glycol column (HP Innowax) of 60 m length, 250 µm i.d. and 0.25 µm film thickness. The oven temperature was kept at 60 °C for the first 10 min, and increased at a ramp rate of 4 °C/min up to 220 °C and held for 10 min and then ramped at 1 °C/min to 250 °C. Helium was used as carrier gas at a constant flow of 1.2 ml/min. The percentage composition of the individual components was obtained from electronic integration measurements using flame ionization detection (FID). All relative percentages of each acid methyl ester sample determine by GC were the mean value of three runs.

2.4 Diesel engine experimental set-up and test procedure

The engine experimental investigation was carried out in the laboratory of the department of Energy Engineering, Budapest University of Technology and Economics (BUTE), Budapest, Hungary. Figure 1, tables 1 and 2 depict the experimental rig, details of the engine's technical specifications and accuracy of the measuring instruments and equipment, respectively. From figure 1, it can be seen that the engine was directly coupled to the Borgghi and Saveri (FE-350S) dynamometer to provide the brake load. Computer was installed to control engine throttling and dynamometer settings. The fuel flow was measured using a fuel balance meter (model: AVL-7030). Engine oil, cooling water, exhaust gas, and inlet air temperatures were measured using a K-type thermocouple with accuracy of ±1.1 °C. All sensors were connected to a computer installed with LabVIEW software for data acquisition. Fuel was introduced from a fuel tank equipped with a flow measurement system. During fuel switching, the fuel tank was drained from the engine fuel filter, new fuel was introduced into the tank until the fuel filter was full, and the engine was then started and allowed to run for a few minutes to clear fuel lines and stabilise. The exhaust emissions were measured using a Horiba MEXA 8120-F gas analyser. In this equipment, the CO measuring instrument uses non-dispersive infrared detectors, NDIR (AIA-23), the NO_x analyser uses a heated chemiluminescence detector, CLD (CLA-53M), and the THC analyser uses a heated flame ionization detector, FID (FIA-22). Smoke was measured using a smoke meter, type: AVL 415 (variable sampling) which was connected before the oxidative converter at the engine exhaust pipe. The exhaust emission system was linked to the computer where emissions data were continuously recorded. In the present study, the engine was run at constant speed of 3000 rpm and different loads, from a low idle to 100 % load at intervals of 25 %. The samples tested in the present study included diesel (D2)

which was used as baseline for comparison purposes, B20 (a blend of 20 % JOME and 80 % diesel), JOME (fresh and untreated jatropha biodiesel) and JOME + PY1000 (fresh jatropha oil dosed with 1000 ppm of antioxidant PY).

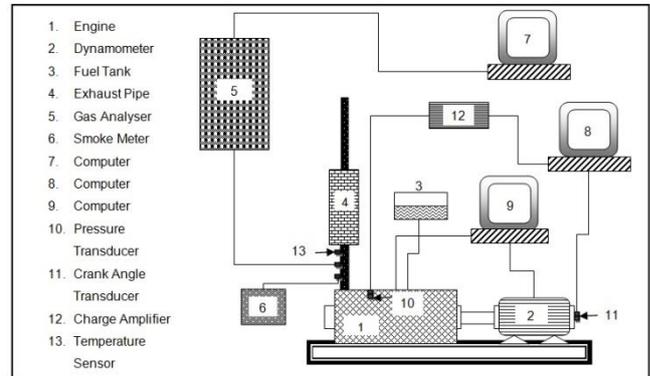


Figure 1: Engine test experimental setup⁴

Table 1: Audi, 1.9 L TDI engine details⁴

Engine Model	Audi, 1.9 L, TDI
Capacity	1896 cm ³
Bore	79.5 mm
Stroke	95.5 mm
Compression Ratio	19.5:1
Maximum Power	66 kW, at 4000 rpm
Maximum Torque	202 Nm ,at 1900 rpm
Fuel System	Direct Electronic Distributor Injection Pump

Table 2: Accuracy of the measuring instruments and equipment

Description	Specification/type	Accuracy
Eddy current dynamometer	Borgghi & Saveri (FE-350S)	±1,13 Nm, ±1 RPM
Fuel mass-flow meter	AVL-7030 Fuel Balance	± 20 g/h
Exhaust gas analyser system	HORIBA MEXA-8120 F	
CO : analyser	AIA-23, NDIR	± 0,002 V/V %
THC : analyser	FIA-22, H FID	± 2,1 ppm
NO _x : analyser	CLA-53, H CLD	± 42 ppm
Smoke meter	AVL 415	±3 mg/m ³
Fuel temperature controller	-	±5 °C
Intake air temperature Controller	-	±5 °C
Temperature sensor	K-type thermocouple	±1.1 °C

3 Results and Discussion

3.1 Properties of JOME

The fatty acid composition, physical and chemical properties of JOME are as depicted in tables 3 and 4 respectively. From table 3, it can be seen that, JOME was rich in unsaturated fatty acid methyl esters, displaying monounsaturated and polyunsaturated fatty acid methyl esters of 41.9 % and 35.6 % respectively. The oleic methyl ester (C18/1) and linoleic methyl ester (C18/2) were the dominant unsaturated fatty acid methyl esters in JOME, the former was 41.1 % and the latter was 35.4 %. From table 4, it was observed that, most of the fuel related properties of JOME were within limits as outlined in the global biodiesel standards such as ASTM D6751 and EN 14242. However, the kinetic viscosity and density of JOME were higher compared to that of diesel; this was possibly due to its high molecular mass and large chemical structure compared to that of mineral diesel⁵. Also, JOME recorded higher cetane number (59.5) than that of diesel (54.6). The cetane number is the most significant property for measuring the ignition quality of fuels for compression ignition diesel engines¹⁷. Also, it was seen that cetane number of diesel (54.6) used in the present study was slightly higher, an indication that it was likely to have a cetane-number enhancing additive in it. The chemical structure of fatty acid methyl esters leads to a higher cetane number of biodiesel compared to petro-diesel^{5, 17}. The initial oxidation stability of fresh produced JOME was 3.87 h as depicted in table 2, which did not meet the minimum requirement of oxidation stability of biodiesel prescribed in EN 14242 and South African standard (SANS 1935) of 6 h. The lower induction period recorded by JOME possible was attributable by high percentage of polyunsaturated fatty acid methyl esters (35.6 %) which are prone to oxidation¹¹. However, JOME recorded oxidation stability above limits as specified in the ASTM D6751 of 3 h; this was associated by the presence of reasonably saturated fatty acid methyl esters (22.2 %) whereby the palmitic methyl ester (C16/0) was the dominant saturated fatty acid methyl ester with 14.7 %.

Table 3: Fatty acid composition of JOME

Fatty acid composition (wt. %)	
Myristic methyl ester (C14/0)	0.2
Palmitic methyl ester (C16/0)	14.7
Palmitoleic methyl ester (C16/1)	0.7
Stearic methyl ester (C18/0)	7.3
Oleic methyl ester (C18/1)	41.1
Linoleic methyl ester (C18/2)	35.4
Linolenic methyl ester (C18/3)	0.2
Arachidic methyl ester (C20/0)	-
Eicosenoic methyl ester (C20/1)	0.1
Eicosadienoic methyl ester (C20/2)	-
Saturated fatty acid methyl esters (SFA)	22.2
Monounsaturated fatty acid methyl esters (MUFA)	41.9
Polyunsaturated fatty acid methyl esters (PUFA)	35.6

Table 4: Fuel properties of JOME and mineral diesel with biodiesel standards

Property	Units	JOME	Diesel	ASTM D6751	EN 14214
Density @ 15 °C	Kg/m ³	876	840	--	860-900
Viscosity @ 40 °C	mm ² /s	4.97	2.67	1.9-6.0	3.5-5.0
Acid value	mgKOH/g	0.19	--	0.8 max	0.5 max
Flash point	°C	177	--	130 min	>101
Lower Heating value	MJ/kg	38.84	42.75	--	--
Lubricity	µm	229	--	--	--
Cetane number	-	59.5	54.6	47 min	51
Cloud point	°C	1	-17	Report	--
Pour point	°C	-2	-19	--	--
CFPP	°C	-6	-20	Report	--
Free glycerol	% mass	0.018	--	0.02 max	0.02 max
Total glycerol	% mass	0.20	--	0.24 max	0.25 max
Water content	% vol.	0.045	0.05	0.05 max	--
Oxidation stability @ 110 °C	h	3.87	--	3 min	6 min

3.2 Influence of antioxidant on the oxidation stability, kinematic viscosity and cetane number of JOME

JOME was doped with antioxidant PY at the concentration of 200, 500, 700 and 1000 ppm to investigate its influence on oxidation stability and other basic fuel related properties (kinematic viscosity and cetane number). From figure 2, it can be seen that, the oxidation stability of JOME increased with the increase of the dosage of antioxidant PY. It required only 200 ppm of antioxidant PY for the oxidation stability of JOME to be 15.1 h, well above minimum requirement of biodiesel oxidation stability as prescribed in EN14112 and SANS 1935 of 6 h. This was because as the concentration of antioxidant increased, the retardation of oxidation process became higher due to the decreased rate of peroxide formation. Thus, it is possible to store biodiesel for long period only when it is doped with antioxidant¹⁸. Since biodiesel is mixed with antioxidants to improve the oxidation stability and to enhance the market acceptance, it is quite possible that these antioxidant additives may affect other fuel properties of biodiesel such as cetane number and kinematic viscosity¹⁶.

Figure 3 depicts the influence of antioxidant additive on kinematic viscosity and cetane number of JOME. It was observed that, additional of antioxidant PY in JOME slightly decreased the kinematic viscosity. The determined kinematic viscosity of JOME (4.97 mm²/s) decreased to 4.1 and 3.7 at 200 and 500 ppm of PY, respectively, this possible was because the peroxide formation decreases with increase in antioxidant concentration. Due to decrease in the rate of peroxide formation the rate of increase of viscosity also became lower^{18,19}. It should be noted that, peroxide formation/oxidation instability can lead to the formation of oxidation products like aldehydes, alcohols, shorter chain

carboxylic acids, insolubles, gum and sediment in the biodiesel, hence increases the kinematic viscosity of biodiesel¹⁹. However, at high concentration of antioxidant PY (700 and 1000 ppm), the kinetic viscosity slightly increased but were still lower than that of untreated JOME. For example at 1000 ppm, the kinematic viscosity of JOME was 3.9 and 4.4 mm²/s, respectively. Also, increase in concentration of antioxidant PY slightly improved the cetane number of JOME. The cetane number of JOME without antioxidant (59.5) improved to 59.8 at 200 ppm dosage and to 60.3 at 1000 ppm. Therefore, it can be seen that, adding antioxidants to improve oxidation stability of JOME also had positive impact on kinematic viscosity (decreased) and cetane number (slightly increased) as an added advantage. Similar observations were previously reported in the literature^{4,5,7,19}.

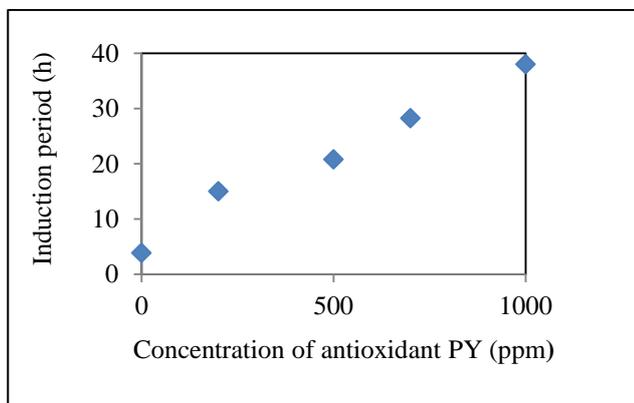


Figure 2: Impact of antioxidant additive (PY) on oxidation stability of JOME

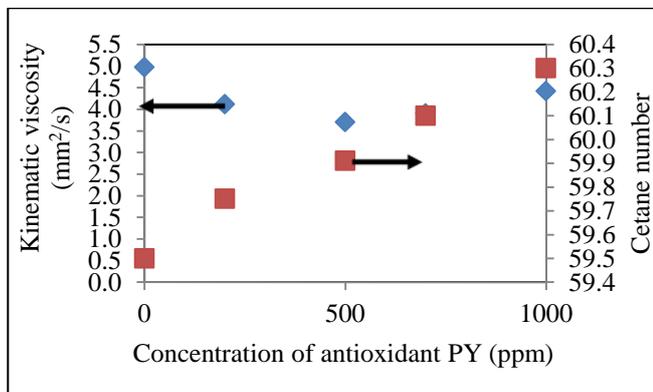


Figure 3: Impact of antioxidant additive (PY) on kinematic viscosity at 40 °C and cetane number of JOME

3.3 Engine performance

3.3.1 Brake specific fuel consumption (BSFC)

BSFC is defined as the fuel consumption rate divided by its corresponding engine power output⁴. Figure 4 illustrates the BSFC of the fuel samples tested with respect to different engine loads at constant engine speed (3000 rpm). From the results, it was observed that, the BSFC decreased with the increase of engine load. Mineral diesel (D2) had the lowest BSFC at all engine loads; it was 11.67 % lower than that of JOME at full load. The higher BSFC of JOME and JOME + PY1000 means that more fuel was consumed and less power

was produced⁴. This was expected because of the lower heating value of JOME and JOME + PY1000 compared to D2 which was approximately 10.5 % less than that of D2, also its higher density contributed to its higher BSFC. These results are in agreement with previous investigators^{6,7,20}. In addition, the BSFC of the treated biodiesel (JOME + PY1000) was slightly less than that of untreated JOME possible because it recorded slightly lower kinematic viscosity than untreated JOME, a finding which concurred with previous studies^{4,6}.

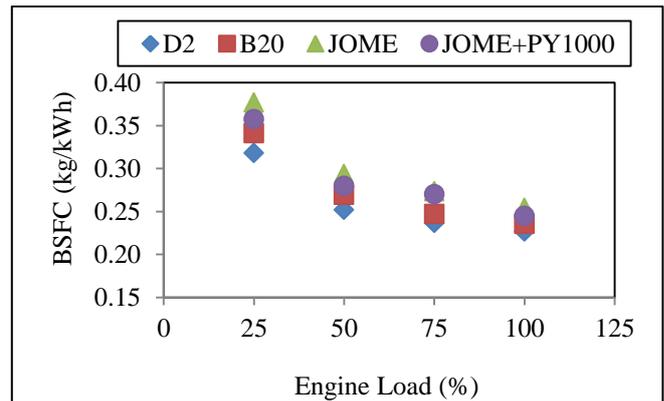


Figure 4: BSFC versus engine load

3.3.2 Brake specific energy consumption (BSEC)

The BSEC is a more reliable factor for comparing different fuels with different heating values and different values of density⁴. From the results, it was observed that, the BSEC decreased as the engine load increased as shown in figure 5. The BSEC value of D2 at full load was 9.0 MJ/kWh slightly lower than that of B20 (9.2 MJ/kWh). It was seen that, at full load the maximum value of BSEC was recorded by JOME (9.7 MJ/kWh), which was slightly higher compared to that of treated biodiesel/JOME+PY1000 (9.5 MJ/kWh). The higher BSEC recorded by biodiesel samples (JOME and JOME+PY1000) compared to that of D2 and B20 was possibly due to its high oxygen content and low heating value^{4,6}.

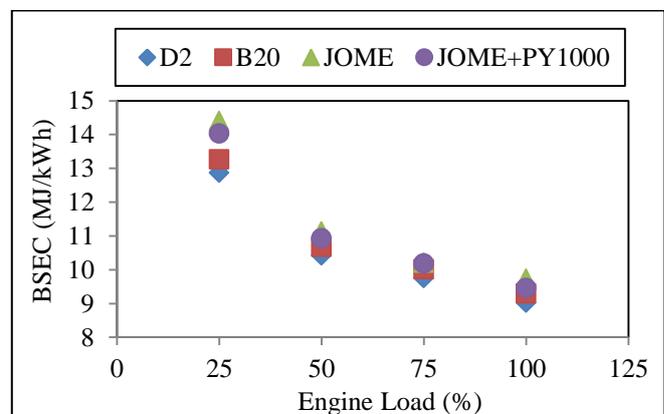


Figure 5: BSEC versus engine load

3.3.3 Brake thermal efficiency (BTE)

From figure 6, it can be seen that, BTE increased with the increase of engine load for all the four samples tested in the

present study. BTE for biodiesel samples was lower compared to diesel; this was due to the higher BSFC of biodiesel⁴. At full load, the maximum brake thermal efficiency obtained was 38.5 %, 37.5 %, 37.0 % and 36.6 % for D2, B20, JOME + PY1000 and JOME respectively. The drop in thermal efficiency with biodiesel samples can be attributed by its lower calorific value resulting in higher fuel supply for a given load which produces slower combustion times and counteracts the possible benefit of the presence of fuel borne oxygen in enhancing the combustion process^{4,20}. In addition, the treated biodiesel (JOME + PY1000) recorded slightly higher BTE than untreated JOME; this possible was associated with slightly lower BSFC displayed by JOME + PY1000 sample⁶.

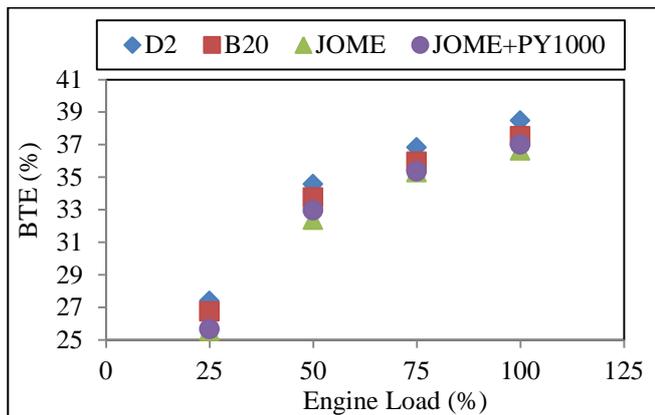


Figure 6: BTE versus engine load

3.4 Exhaust emissions

3.4.1 Oxides of nitrogen (NOx)

High temperatures and high oxygen concentrations plays a key role in NOx formation⁹. Extreme increases in NOx emissions emerge when maximum combustion temperatures exceed 1800 K in the diesel engine cylinders. The formation of NOx is highly dependent upon the compression ratio, geometry of the combustion chamber (related to the velocity of flame propagation), equivalence ratio, pressure and temperature of inlet air, fuel injection advance, chemical properties of fuel, and percentage of waste gas in fresh inlet air⁹. The results for the four samples investigated in the present study on NOx emissions are as shown in figure 7. It was observed that, the NOx emissions increased as the engine load increased for all the samples, this was because the temperature in the cylinder also increased as the engine load increased and thus higher absolute NOx formation⁴. However, biodiesel samples displayed slightly higher NOx emissions compared to D2 and B20 especially at higher engine loads, this was associated with the intrinsic oxygen content in the biodiesel samples; approximately 11 % have been reported in the literature⁴. The fuel with oxygen may provide additional oxygen for the formation of NOx^{4,6,9}. Also, higher cylinder pressure could contribute to the increased NOx emissions, due to the increased peak combustion temperature at higher engine loads⁶. From figure 7, it was also seen that, NOx emissions were slightly higher with JOME at all engine loads compared to JOME+PY1000 which was approximately 0.97 % higher at

full engine load. The findings concurred with previous studies^{4,9}.

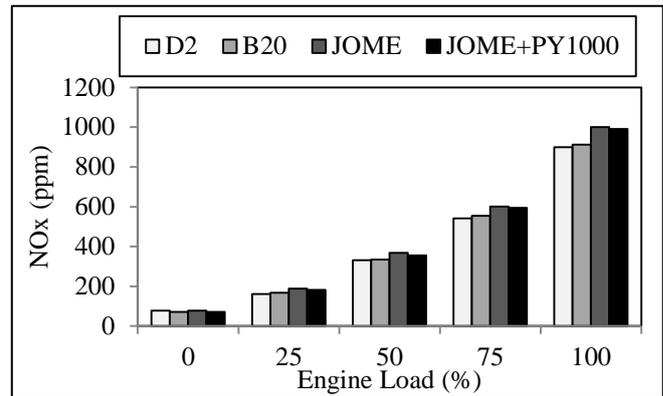


Figure 7: Variations of NOx emissions versus engine loads

3.4.2 Carbon monoxide (CO)

The chemical products of a complete combustion reaction of hydrocarbon based fuels are CO₂ and H₂O. On the other hand, CO is a product of incomplete combustion related to high equivalence ratio and low oxygen concentration in combustion chamber of a diesel engine⁹. The formation of CO versus engine load for the four sample tested in this study is shown in figure 8. The results indicated that, the CO emissions decreased with the increase of engine load for the all four samples. This was because at higher engine loads, the higher combustion temperature promotes more complete combustion and hence less CO emission⁴. The high CO emissions were observed at lower loads, with the lowest emissions recorded at 75 % engine load. At the full engine load B20, JOME and JOME + PY1000 evidenced slightly higher CO emission compared to D2. This possible was because of relatively poor atomization and lower volatility of biodiesel samples compared to diesel⁴. In addition, at lower engine loads, CO emissions were higher due to incomplete combustion, whereas at full engine load (100 %) CO emissions were slightly higher compared to 75 % load, due to the local presence of a richer mixture in the combustion chamber. The results of these CO emissions are in good agreement with those reported in the literature^{4,6}. However, there were no significance differences between biodiesel samples with and without antioxidants.

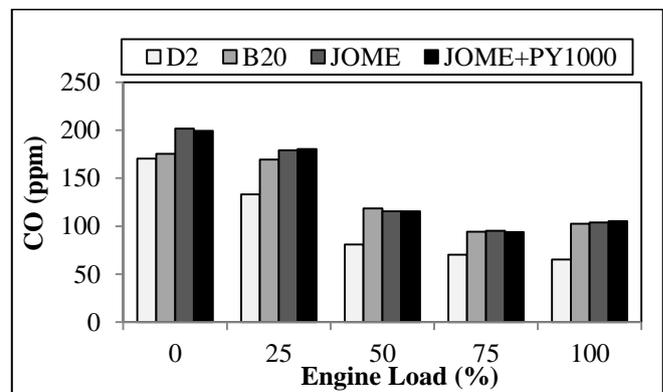


Figure 8: Variations of CO emissions versus engine loads

3.4.3 Total hydrocarbons (THC)

The total hydrocarbons (THC) emission is basically affected by engine operating conditions, fuel properties, and fuel spray characteristics¹⁰. There two major causes of THC emissions in the diesel engines which include (1) mixing of fuel so that it is leaner than the lean combustion limit during the delay period; (2) under-mixing of fuel, which leaves the fuel injector nozzle late in the combustion process at low velocity¹⁰. The variation of THC emissions with loads is shown in figure 9. It was seen that, there was a slight decrease in ppm of THC when the diesel engine was fuelled with biodiesel samples at all engine loads except at idle stage where biodiesel sample displayed slightly higher THC emissions. The higher THC at idle condition possible was attributed by the worse combustion process of biodiesel due to higher viscosity and lower temperature⁴. The lower THC emissions was displayed at intermediate engine loads (50 % and 75 %) with biodiesel samples (JOME and JOME + PY1000) producing the mean reduction of 17.7 % and 23.2 % respectively than D2 at engine load of 75 %. The oxygen content of biodiesel might have provided some advantageous conditions during air–fuel interactions, particularly in the fuel-rich regions, which enhanced the oxidation of unburned THC, thus reducing THC significantly¹⁰. In addition, there were no significant differences in THC emissions between biodiesel samples with and without antioxidant additive.

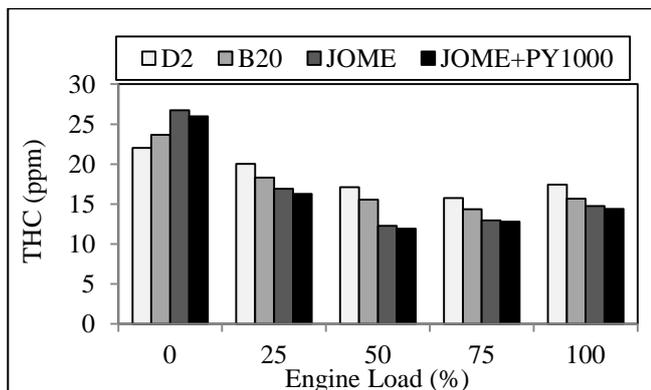


Figure 9: Variations of THC emissions versus engine loads

3.4.4 Smoke

Diesel fuel recorded higher smoke emissions at all engine loads compared to biodiesel samples as depicted in figure 10. It was also observed that, the maximum smoke emissions for all four samples were at full engine load (100 %) where diesel sample recorded the maximum value of 63 mg/m³ while JOME and JOME + PY1000 displayed lower values of 25 and 23 mg/m³ respectively. The lower smoke emission of biodiesel samples compared to diesel possible was due to its oxygenated nature where more oxygen is available for burning and reducing smoke emission in the exhaust^{4,10,20}. However, there were slight differences in smoke emissions between biodiesel samples with and without antioxidants, biodiesel with antioxidants displaying slightly lower smoke emissions; this possibly was attributed by non-uniform combustion process between JOME and JOME + PY1000 biodiesel samples^{4,10}.

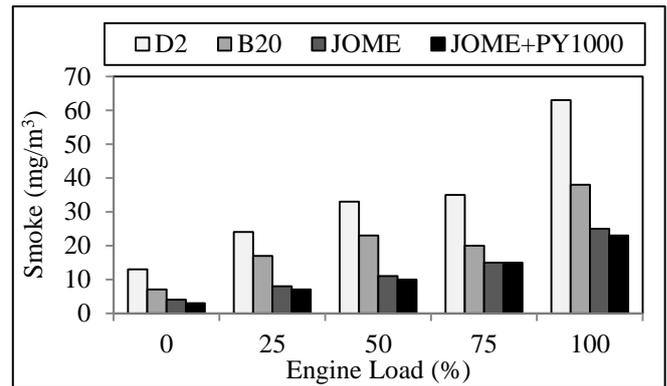


Figure 10: Variations of smoke emissions versus engine loads

4 Conclusion

The effect of antioxidant additive on oxidation stability, kinetic viscosity, cetane number, engine performance and exhaust emissions of diesel engine fuelled with biodiesel made from jatropha oil of Eastern Africa origin have been studied in this work. The oxidation stability was observed to increase with the increase of dosage of antioxidant PY. It required only 200 ppm for the oxidation stability of JOME to meet minimum requirement of oxidation stability prescribed in EN14112 and SANS 1935 of 6 h. The kinematic viscosity slightly decreased while cetane number slightly increased with increase of dosage of antioxidant PY. Also, brake specific fuel consumption (BSFC) of JOME with antioxidant decreased more than that without antioxidant, but both were higher than that of diesel and B20. Additionally, emissions of CO and NOx were slightly higher for biodiesel samples than mineral diesel. THC was found to be reduced at intermediate load and more for biodiesel while smoke was lower for biodiesel at all loads than diesel fuel. Addition of 1000 ppm of antioxidant PY to biodiesel displayed few effects on the exhaust emissions. In summary, the biodiesel derived from non-edible jatropha oil of Eastern African origin without or with antioxidant additives can be utilized as partial substitute for mineral diesel. However, further research is required to evaluate the influence of JOME doped with antioxidant on the combustion characteristics of a CI engine especially with regard to the heat release and cylinder pressures.

Acknowledgements

Funds from National Research Foundation (NRF), South Africa, Tshwane University of Technology and Hungarian/South African Intergovernmental S&T Cooperation Programme (Grant: ZA-17/09) to support this study are gratefully acknowledged.

References

- Demirbas A, Progress and Recent Trends in Biofuels. *Progress in Energy and Combustion Science*, 2007, 33(1), 1-18.
- Demirbas A, Political, Economic and Environmental Impacts of Biofuels: A Review. *Applied Energy*, 2009, 86(1), S108–S117.

3. Agarwal AK, Biofuels (Alcohols and Biodiesel) Applications as Fuels for Internal Combustion Engines, *Progress in Energy and Combustion Science*, 2007, 33(3), 233-271.
4. Kivevele TT, Kristóf L, Bereczky A and Mbarawa MM, Engine Performance, Exhaust Emissions and Combustion Characteristics of a CI Engine Fuelled with Croton Megalocarpus Methyl Ester with Antioxidant, *Fuel*, 2011, 90(8), 2782–2789.
5. Kivevele T and Huan Z, Effects of Antioxidants on the Cetane Number, Viscosity, Oxidation Stability, and Thermal Properties of Biodiesel Produced from Non-edible Oils, *Energy Technology*, 2013, 1(9), 537 – 543.
6. Ryu K, Effect of Antioxidants on the Oxidative Stability and Combustion Characteristics of Biodiesel Fuels in an Indirect-injection (IDI) Diesel Engine, *Journal of Mechanical Science and Technology*. 2009, 23(11), 3105-3113.
7. Ryu K, The Characteristics of Performance and Exhaust Emissions of a Diesel Engine Using a Biodiesel with Antioxidants. *Bioresource Technology*, 2010, 101(1), S78-S82.
8. Ileri E and Koçar G, Effects of Antioxidant Additives on Engine Performance and Exhaust Emissions of a Diesel Engine Fueled with Canola Oil Methyl Ester–diesel Blend, *Energy Conversion and Management*, 2013,76,145–154.
9. Ileri E and Koçar G, Experimental Investigation of the Effect of Antioxidant Additives on NOx Emissions of a Diesel Engine Using Biodiesel, *Fuel*, 2014, 125, 44-49.
10. Fattah IMR, Masjuki HH, Kalam MA, Mofijur M and Abedin MJ, Effect of Antioxidant on the Performance and Emission Characteristics of a Diesel Engine Fueled with Palm Biodiesel Blends. *Energy Conversion and Management*, 2014, 79, 265 – 272.
11. Kivevele TT, Mbarawa MM, Bereczky A, Laza T, and Madarasz J, Impact of Antioxidant Additives on the Oxidation Stability of Biodiesel Produced from Croton Megalocarpus Oil, *Fuel Processing Technology*, 2011, 92(6), 1244–1248.
12. Sarin R, Sharma M, Sinharay S and Malhotra RK, Jatropha-palm Biodiesel Blends: An Optimum Mix for Asia, *Fuel*, 2007, 86(10), 1365-1371.
13. Berchmans HJ and Hirata S, Biodiesel Production from Crude Jatropha Curcas L. Seed Oil with a High Content of Free Fatty Acids, *Bioresource Technology*, 2008, 99(6), 1716-1721.
14. Tiwari AK, Kumar A and Raheman H, Biodiesel Production from Jatropha Oil (Jatropha Curcas) with High Free Fatty Acids: An Optimized Process, *Biomass and Bioenergy*, 2007, 31(8), 569-575.
15. Ramadhas AS, Jayaraj S and Muraleedharan C, Biodiesel production from high FFA rubber seed oil, *Fuel*, 2005, 84,(4), 335-340.
16. Kivevele TT and Huan Z, An Analysis of Fuel Properties of Fatty Acid Methyl Ester from Manketti Seeds Oil, *International Journal of Green Energy*, 2015, 12(4), 291–296.
17. Wadumesthrige K, Smith J, Wilson J, Salley S and Simon KY, Investigation of the Parameters Affecting the Cetane Number of Biodiesel, *Journal of the American Oil Chemists' Society*, 2008, 85(11), 1073-1081.
18. Das LM, Bora DK, Pradhan S, Naik MK and Naik SN, Long-term Storage Stability of Biodiesel Produced from Karanja Oil, *Fuel*, 2009, 88(11), 2315-2318.
19. Jain S and Sharma MP, Long Term Storage Stability of Jatropha Curcas Biodiesel, *Energy*, 2011, 36(8), 5409-5415.
20. Aliyu B, Shitanda D, Walker S, Agnew B, Masheiti S and Atan R, Performance and Exhaust Emissions of a Diesel Engine Fuelled with Croton Megalocarpus (Musine) Methyl Ester, *Applied Thermal Engineering*, 2011, 31(1), 36-41.