Engine emissions and combustion analysis of biodiesel from East African countries

AUTHOR:
Paul Maina[1,2]

AFFILIATIONS:
[1]Department of Mechanical Engineering, Tshwane University of Technology, Pretoria, South Africa

[2]Department of Mechanical and Production Engineering, Moi University, Eldoret, Kenya

CORRESPONDENCE TO:
Paul Maina

EMAIL:
mainap@tut.ac.za

POSTAL ADDRESS:
Department of Mechanical Engineering, Tshwane University of Technology, Private Bag X680, Pretoria 0001, South Africa

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Environmental, availability and financial problems associated with fossil fuels encourage the manufacture and use of biodiesel. In this study, vegetable oil was extracted from *Jatropha curcas* seeds sourced from Kenya and Tanzania. A two-step acid–base catalytic transesterification process was used to produce biodiesel because of the amount of free fatty acids present in the oil. The test rig used in the experiments was an Audi, 1.9-litre, turbocharged direct injection, compression ignition engine. Emissions were measured using an Horiba emission analyser system while combustion data was collected by a data acquisition system, from which cylinder pressure and rate of heat release of the test engine in every crank angle were calculated. The two biodiesels showed better emission characteristics than the fossil diesel included in the tests for comparison purposes. Cylinder pressure and heat release of the biodiesel were also within acceptable ranges. However, the emission and combustion characteristics differed between the two biodiesels – a result likely related to their different origins. These findings prove that the source of biodiesel is an important factor to consider.

Introduction

Fuel combustion

Any material that can be burned to release thermal energy is called a fuel. Most familiar fuels consist primarily of hydrogen and carbon, and as such are called hydrocarbon fuels and exist in all phases. Combustion is a chemical reaction during which a fuel is oxidised and a large quantity of energy is released. The combustion process takes place in a controlled manner. The oxidiser most often used in combustion processes is air because it is free and readily available. Pure oxygen (O_2) is used as an oxidiser only in some specialised applications, such as cutting and welding, for which air cannot be used. A fuel must be brought above its ignition temperature to start combustion and the proportions of the fuel and air must be in the proper range for combustion to be initiated.

All combustible components of a fuel are burned to completion during a complete combustion process. The combustion process depends on many different parameters, such as the volume of injected fuel, the timing of ignition delay and air charge mixtures. In diesel engines, the timing of fuel injection is a major parameter that affects the combustion and exhaust emissions. If the injection of fuel begins earlier, the initial air temperature and pressure are lower; as a result, the ignition delay will be longer. If the injection starts later (when the piston is closer to the top dead centre), the initial air temperature and pressure are higher and, consequently, the ignition delay is shorter. Hence, the variation in injection timing exerts a major influence on the engine performance and exhaust emissions. Emissions from the combustion of these fuels are carbon dioxide (CO_2), carbon monoxide (CO), unburnt hydrocarbons, nitrogen oxides (NO_x), particulate matter, sulphur dioxide (SO_2) and other toxic compounds. The amount and type of emissions attributable to fuel combustion depend very much on the type of fuel burned.

Why biodiesel

Environmental protection laws continue to be more and more stringent, thus making the use of fossil fuels less favourable. These laws, in addition to the scarcity of fossil fuel which increases its cost, have prompted researchers and industries to search for new and better fuels. Biodiesel, a mixture of mono alkyl esters of long-chain fatty acids, derived from renewable lipid feedstock, such as vegetable oil or animal fat, is one of the alternative fuels which has received a lot of attention because it can be used in diesel engines without major modifications. It offers many advantages in that it is renewable, energy efficient, non-toxic, sulphur free and biodegradable and it burns more cleanly. Indirectly, by encouraging the planting of trees which consume the CO_2 produced during combustion, the use of biodiesel also reduces global warming gas emissions. Biodiesel as a fuel is important, especially in the rural areas of agriculturally developing countries like Kenya and Tanzania where there is vast unutilised land and a lack of modern forms of energy. Information on the production and characterisation of biodiesel from these countries is sparse.

Factors influencing biodiesel properties

It is known that the type of biodiesel produced from vegetable oil depends on the type of vegetable oil and its geographical location. For instance, several researchers have found that jatropha oil produces a superior biodiesel to that of many other non-edible feedstocks.[1-3] Many researchers also have observed different characteristics in biodiesels produced in the same way from similar plants from different regions. For example, Emil et al.[4] compared jatropha seed oil from Malaysia, Indonesia and Thailand which was produced in the same way using the same facilities, and found that the physicochemical characteristics of the oil produced were very different; the free fatty acid content, iodine value, saponification value, oil content and density were different in oils from different regions. Lu et al.[5] produced biodiesel from jatropha oil originating in China and observed that the properties of the crude jatropha oils varied with their region of origin in China. They stated that, because fatty acid content affects the biodiesel production process and the biodiesel fuel properties, jatropha oils from different origins which have different fatty acid contents, leads to biodiesels with different properties.

In the same context, Foidl et al.[6] produced jatropha oil from seeds which hailed from Cape Verde and Nicaragua. The seeds were processed in a similar manner. The oils were produced using the same equipment and in a similar environment. Still, the properties and content characteristics of the produced oils were different. The difference was conspicuous, ranging from the composition of the dried seeds to the saponification number, viscosity, free fatty acid content and iodine number. Vegetable oils other than jatropha oil have shown similar results: Lalas and Tsaknis[7] compared the characteristics of oils from *Moringa oleifera* of Indian origin and Kenyan (Mbololo) origin and found that, even though the oil extraction and processing procedure were identical, the properties of the oils differed according to the regions from which they were sourced. In addition to the *Jatropha* tree having excellent adaptation capacity, jatropha oil produces superior biodiesel compared with those of many other non-edible feedstocks, which is why it was used in this study.

Aim

Plants from different regions produce oils with characteristics which vary by wide margins and depend more on the regions in which the plants are grown than the species from which the oils are derived, most probably as a result of the environmental conditions to which they are exposed. It is thus very important to study the potential, characteristics and operation of biodiesel produced from a plant (e.g. *Jatropha*) originating from a different region. In this study, two biodiesels were produced – in the same lab using the same chemicals and equipment – from jatropha oil from two neighbouring East African countries. The characteristics of the two biodiesels were compared in terms of emissions and combustion. To understand and optimise the combustion process, a careful analysis of cylinder pressure and heat release was performed, which furnished precise information about the combustion process.

Materials and equipment

Materials

Samples of *Jatropha curcas* oil were supplied from Kenya (Jatropha A) and Tanzania (Jatropha B), respectively. The oils were produced from the seeds by the same mechanical oil extraction method. The chemicals used were analytical-grade reagents: potassium hydroxide and methanol, at 85% and 99.5% purity, respectively, and were purchased from local suppliers.

Biodiesel production process

The transesterification process was chosen for biodiesel production in this study, and the experiments were conducted using beakers as reactors. The reaction beaker was placed on a thermostatically controlled heating plate equipped with a magnetic stirrer whose maximum heating capacity is 420 °C and maximum agitation is 2000 rpm. A thermometer was fixed by the use of a retort stand and immersed in the beaker for verifying the temperature of the heating plate. The free fatty acid content was determined using the simple titration method as reported in the literature.[8]

The free fatty acid content of jatropha oils in this study was initially found to be 5.6% for Jatropha A and 5.8% for Jatropha B. An acid esterification process followed by the transesterification method was then used to prepare the *Jatropha curcas* methyl esters. The acid pre-treatment process was used to convert free fatty acids to esters using an acid catalyst (H_2SO_4) to reduce the free fatty acid concentration of the oil to below 1%. The acid catalyst (w/w of oil: 0.5% H_2SO_4) and a 6:1 methanol: oil molar ratio was used and the mixture stirred at 500 rpm for 1 h at 50 ºC. The mixture was allowed to settle, after which the pre-treated oil was collected and purified.[9] After acid esterification, transesterification was carried out at the following standard conditions: 6:1 methanol/oil molar ratio (mol/mol), 1.0 wt% potassium hydroxide, 55–60 °C reaction temperature, 400 rpm agitation speed and 60 min reaction time.[10] After the reaction and settling, the biodiesel (methyl esters) was collected and purified. The final product – the biodiesel – was a clear, light yellow liquid.

Measurement of biodiesel properties

The fuel properties of the samples were tested according to the standards shown in Table 1. All experiments were repeated at least twice and the results recorded when the standard deviation was less than 5%.

Table 1: Methods for determination of fuel properties

Property	Units	Test method
Cetane number	–	ASTM D613
Heating value	MJ/kg	ASTM D240
Density	kg/m^3	ASTM D941
Viscosity	mm^2/s	ASTM D445
Flash point	°C	ASTM D93-94
Water content	%	ISO 12937
Acid value	mg KOH/g	ASTM D974
Cloud point	°C	ASTM D2500
Lubricity	μm	ISO 12156
Oxidation stability	h	EN 14112

The fatty acid composition of biodiesel was analysed using a gas chromatograph mass spectrometer (Agilent 6890N) coupled to an inert mass-selective detector (Agilent 5973). The percentage composition of the individual components was obtained from electronic integration measurements using flame ionisation detection. All relative percentages determined by gas chromatography for each fatty acid sample are the means of three runs.

Emissions and combustion analysis

An Audi, 1.9-litre, turbocharged direct injection (TDI) compression ignition engine (Figure 1) was used to study engine performance. The engine is a four-stroke, four-cylinder, water-cooled diesel engine. The engine's technical specifications are given in Table 2.

Table 2: Details of the experimental engine used

Engine model	Audi, 1.9 L, turbocharged direct injection
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 injection with electronic distributor pump

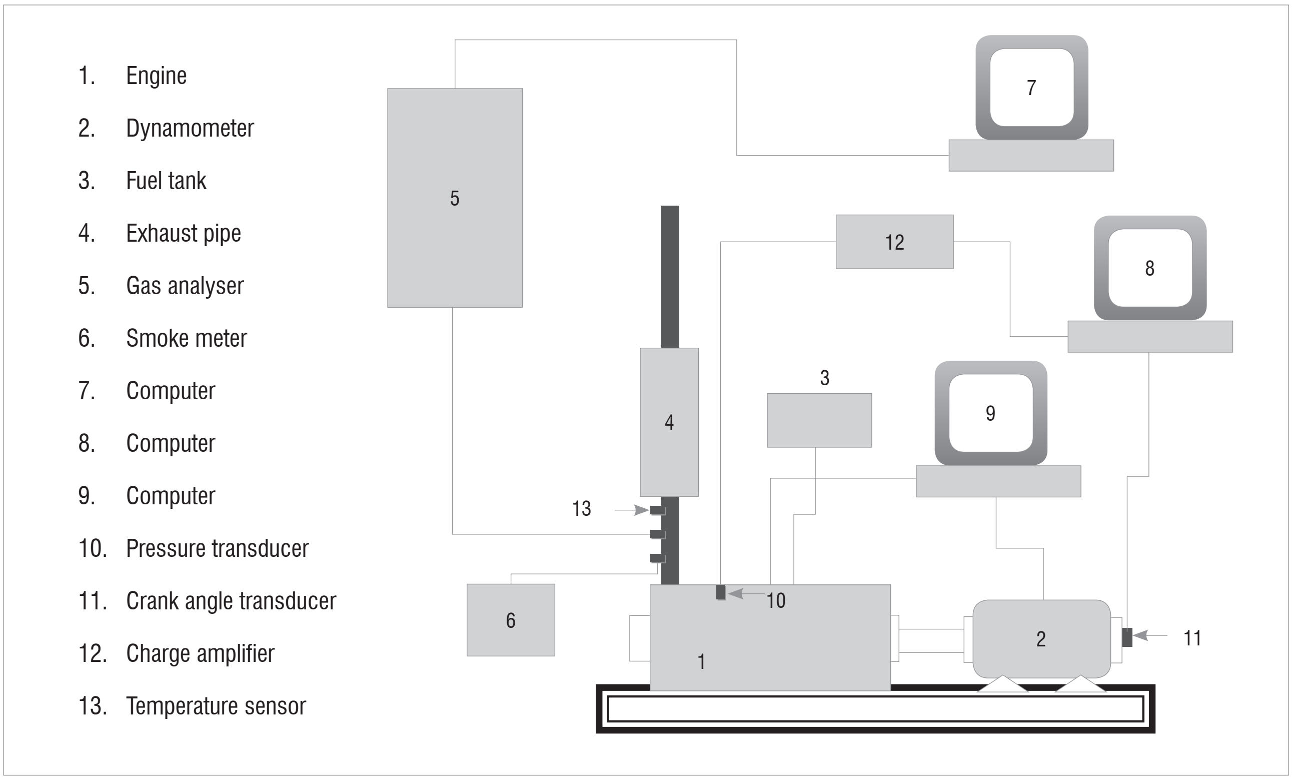

Figure 1: Engine test experimental set-up.

Figure 1 depicts the equipment connections for the engine test. A pressure transducer (10) was installed in one of the piston cylinders. Cylinder pressure signals from the pressure transducer were amplified by a charge amplifier (12) and connected to the SMETech COMBI-PC indication system (8) for data acquisition. The data acquisition system was externally triggered 1024 times in one revolution by an incremental crank angle transducer-optical encoder (11). Fuel was introduced from a fuel tank (3) 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. Emission was measured by an Horiba emission analyser system (5) equipped with analyser modules NDIR (AIA-23), H.FID (FIA-22) and H.CLDC (CLA-53M) for measuring CO, CO_2 and unburnt hydrocarbons; THC; and NO_x, respectively, and by a smoke meter (6) connected before the oxidative converter at the engine exhaust pipe (4). The system was connected to the computer (7) and emission data was recorded.

Heat release calculations

During the engine test, the engine was run at a constant speed (3000 rpm) at different loads, from a low idle to 100% load at intervals of 25% of full load. Heat release was subsequently calculated from cylinder pressure and crank angle readings and emission data was then collected. The net heat release was calculated by a computer program using Equation 1 from pressure data (with respect to the crank angle) and cylinder geometry (with respect to the crank angle). The analysis was derived from the first law of thermodynamics for an open system which is quasistatic.[11]

$$\frac{dQn}{d\theta} = \frac{1}{\gamma\text{-}1}\left(\gamma p\frac{dV}{d\theta} + V\frac{dp}{d\theta}\right)$$

Equation 1

where:

$\frac{dQn}{d\theta}$ = net heat-release rate (J/degree crank angle) and

γ = the ratio of specific heats, $\frac{C_p}{C_v}$

V and $\frac{dV}{d\theta}$ terms are calculated as shown in Equations 2 and 3, respectively:

$$V = V_c + A \times r\left[1 - \cos\left(\frac{\pi\theta}{180}\right) + \frac{1}{\lambda}\left\{1\text{-}\sqrt{1\text{-}\lambda^2\sin^2\left(\frac{\pi\theta}{180}\right)}\right\}\right]$$

Equation 2

and

$$\frac{dV}{d\theta} = \frac{\pi\theta}{180} \times r\left[\sin\frac{\pi\theta}{180} + \frac{\lambda^2\sin^2\left(\frac{\pi\theta}{180}\right)}{2\times\sqrt{1-\lambda^2\sin^2\left(\frac{\pi\theta}{180}\right)}}\right]$$

Equation 3

But $\lambda = \frac{1}{r}$ and $A = \frac{\pi}{4}D^2$

where *l* is the connecting rod length, *r* is the crank radius, *D* is the cylinder bore and V_c is the clearance volume.

Results and discussion

Biodiesel properties

The biodiesel from *Jatropha curcas* (Jatropha A and B) had a fatty acid composition as depicted in Table 3. As seen, the profiles for the two biodiesels are different. Table 4 summarises the properties of methyl esters obtained from the oils, which were found to be within the limits of biodiesel standards (ASTM D6751 and EN 14214), although they were different between the two biodiesels. The properties of fossil diesel are included for comparison purposes.

Table 3: Fatty acid composition of *Jatropha curcas* samples

Fatty acid composition (wt. %)	Jatropha A	Jatropha B
Palmitic methyl ester (C16/0)	15.3	16.1
Palmitoleic methyl ester (C16/1)	1.1	0.8
Stearic methyl ester (C18:0)	6.4	6.8
Oleic methyl ester (C18/1)	40.1	40.8
Linoleic methyl ester (C18/2)	36.9	34.6
Linolenic methyl ester (C18/3)	0.2	0.9
Saturated fatty acid methyl esters	21.7	22.9
Monounsaturated fatty acid methyl esters	41.2	41.6
Polyunsaturated fatty acid methyl esters	37.1	35.5

Table 4: Fuel properties of biodiesels Jatropha A and B, diesel and biodiesel standards

Property	Units	Jatropha fuel		Diesel	ASTM D6751	EN 14214
		A	B			
Density @ 15 °C	kg/m³	855	876	832	–	860-900
Viscosity @ 40 °C	mm²/s	4.33	4.37	3.01	1.9-6.0	3.5-5.0
Acid value	mgKOH/g	0.09	0.10	–	0.8 maximum	0.5 maximum
Flash point	°C	186	188	–	130 minimum	101 minimum
Heating value	MJ/kg	37.82	37.60	42.63	–	–
Lubricity	µm	218	222	–	–	–
Cetane number	–	56.54	55.13	54.60	47 minimum	–
Cloud point	°C	1	2	-16	–	–
Pour point	°C	-3	-2	-19	–	–
Water content	ppm	460	498	50	500 maximum	500 maximum
Sulphur content	ppm	0.0025	0.0020	45		
Oxidation stability at 110 °C	h	9.65	6.51	–	–	minimum

Engine emissions

Engine emissions obtained experimentally were plotted against load as described below.

Oxides of nitrogen

Figure 2 depicts the oxides of nitrogen (NO_x) emissions of the fuel samples tested at different load conditions. In general, the formation of NO_x was affected by the peak flame temperature, the high burning gas temperature, the ignition delay and the content of nitrogen and oxygen available in the reaction mixture.[12] It was observed that as the load increases, the in-cylinder temperature also increases and thus higher absolute NO_x (ppm) formation results. Higher cylinder pressure could contribute to increased NO_x emissions, as a result of the increased peak combustion temperature at higher engine loads. These results correspond to those in the literature.[13,14] Fossil diesel (D2) exhibited slightly higher NO_x emissions compared with Jatropha A, especially at lower engine loads; however, Jatropha B had the highest overall emission of NO_x. A possible reason for this finding may be the slow burning of the more viscous biodiesel, because it spent longer in the high temperature zone.[15] Moreover, the NO_x emission increase can be associated with the oxygen content in the fuel samples as fuel with oxygen may provide additional oxygen for the formation of NO_x.[16]

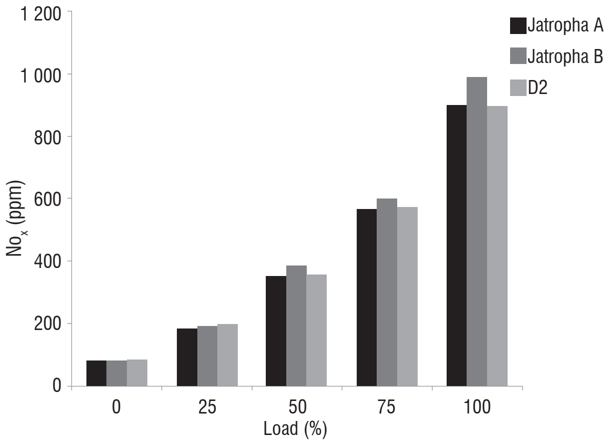

Figure 2: NO_x emissions for the different fuel samples at different loads.

Total hydrocarbons

The variation of THC emissions with load is shown in Figure 3. It can be observed that THC emissions are a maximum on idling, whereas lower THC values are obtained at 50% and 75% loads at steady engine speed. A similar trend was also reported in the literature, that is, high THC emissions were observed at lower loads and maximum loads.[17] The small difference between D2 and the jatropha fuels in THC emissions could possibly be attributed to the higher fuel supply for a given load for jatropha, which produces slower combustion times and counteracts the possible benefit of the presence of fuel-borne oxygen in enhancing the combustion process of the jatropha fuels.[18,19]

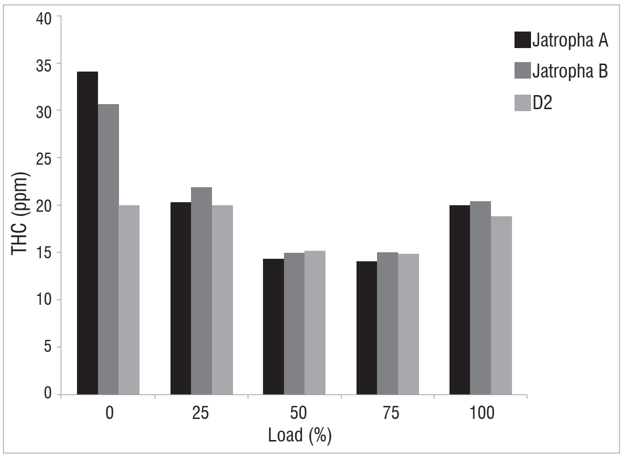

Figure 3: Total hydrocarbon (THC) emissions for the different fuel samples at different loads.

Carbon monoxide

The formation of CO with increasing load is illustrated in Figure 4. The figure shows that CO emission decreases with increasing engine load. High CO emissions were observed at lower loads, with the lowest emissions recorded at 75% of maximum engine load. CO is a product of incomplete combustion; thus at higher engine loads, the high combustion temperature promotes more complete combustion and hence fewer CO emissions. These results are comparable with those reported in the literature.[14,19] The relatively poor atomisation and lower volatility of fuel samples is responsible for this trend. In addition, at lower loads, CO emissions are higher because of incomplete combustion, whereas at 100% load, CO emissions are slightly increased compared with at 75% load, as a result of the local presence of a richer mixture in the combustion chamber.[20]

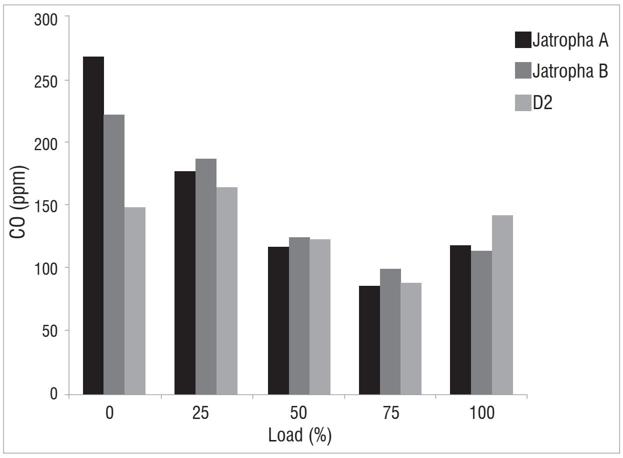

Figure 4: Carbon monoxide (CO) emissions for the different fuel samples at different loads.

Carbon dioxide

Fuel derived from vegetable oils results in fewer CO_2 emissions when used to run diesel engines because plants absorb CO_2 in a sustainable fashion during growth.[21,22] Figure 5 illustrates the CO_2 emissions at different loads for the two biodiesels and fossil diesel. It can be observed that CO_2 emissions increase as the load increases at the same engine speed. Oxygen present in biodiesel supports combustion which leads to higher CO_2 emissions at low loads as a result of complete combustion. The finding that diesel exhibits lower CO_2 emissions has been reported previously.[23] At higher loads, however, poor fuel atomisation and a lower combustion duration override the advantages of bound oxygen in Jatropha A and B, thus incomplete combustion results.

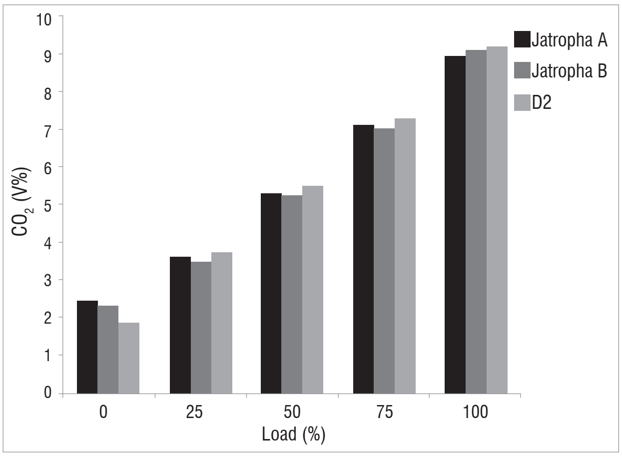

Figure 5: Carbon dioxide (CO_2) emissions for the different fuel samples at different loads.

Smoke

Smoke emissions with increasing load are shown in Figure 6. Diesel fuel exhibited the highest smoke emissions at all loads, whilst Jatropha B exhibited the lowest emissions under the same load conditions. Maximum smoke emission values were observed at 100% load for all fuels. The presence of oxygen in Jatropha A and B samples could explain their lower emission values.[13,24]

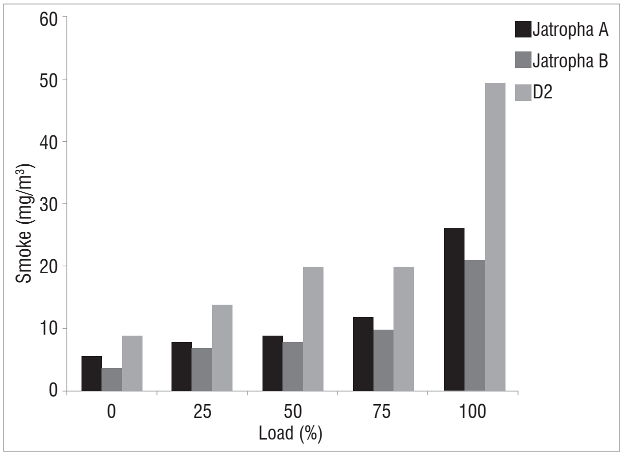

Figure 6: Smoke emissions for the different fuel samples at different loads.

Combustion analysis

Variation in injection timing exerts a major influence on engine performance and exhaust emissions. To understand and optimise the combustion process, a careful analysis of cylinder pressure and heat release was performed, which furnished precise information about the combustion of biodiesel. A TDI compression ignition engine was used to undertake an analysis of the combustion characteristics of the fuel samples tested.

Cylinder pressure

Figure 7 indicates the peak cylinder pressure for different fuels at different engine load conditions. Figure 8 illustrates the variations of cylinder pressure with crank angle degree for the fuels at full load and a constant engine speed of 3000 rpm. Similar trends were obtained at other loads and differed only in the magnitude of the pressure and the corresponding crank angle at which the pressure appeared. In a compression ignition engine, the cylinder pressure depends on the burned fuel fraction during the pre-mixed burning phase, that is, the initial stage of combustion. Cylinder pressure characterises the ability of the fuel to mix well with air and burn. A high peak pressure and maximum rate of pressure rise correspond to a large volume of fuel burned in the pre-mixed combustion stage.[25]

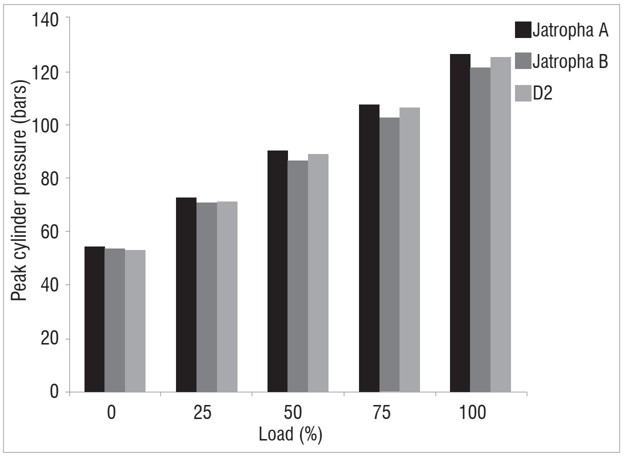

Figure 7: Peak cylinder pressure for the different fuel samples at different loads.

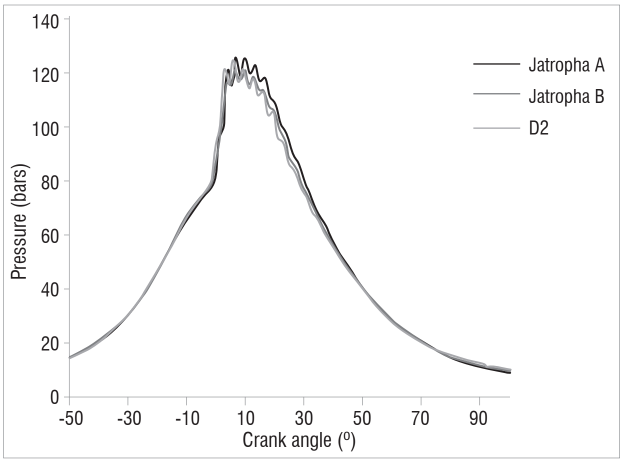

Figure 8: Cylinder pressure variation with crank angle at full load.

It can be noted that Jatropha B produced the lowest peak cylinder pressure while Jatropha A produced the highest at all loads. All fuels exhibited peak cylinder pressures between crank angles of -10° and 10°, with lower load levels exhibiting peak cylinder pressure at negative crank angles and vice versa. It was also observed that the cylinder pressure increases as the load increases. This increase in pressure is to be expected in a TDI diesel engine and is caused by the increased amount of injected fuel and charge pressure in the air intake manifold at higher loads.

The temperature and volume flow of the exhaust gases that pass through the turbo charger influence the characteristics of air flow in the intake manifold, because of the increased spinning speed of the turbocharger turbine and the heat exchange between exhaust gases and the charged air. The amount of air forced into the intake manifold increases as the load increases, because the high temperature, high velocity exhaust gas that passes through the turbocharger turbine causes a rise in the velocity of intake air, which forces more air into the cylinders. The increased amount of air causes larger amounts of fuel to be injected into the cylinder, which in turn increases the cylinder pressure.

Combustion of Jatropha A resulted in the highest peak pressures probably because of the increase in ignition delay associated with using Jatropha A. This ignition delay increases the amount of fuel burned within the pre-mixed burning phase, causing high peak pressures and a high rate of pressure rise. Jatropha A's lower viscosity (compared with Jatropha B) and the contribution of intrinsic oxygen (compared with D2) may also be the reason for the high cylinder pressure. The high viscosity of Jatropha B is the reason for its lower peak cylinder pressure, as fuel spraying is affected by viscosity. Complete combustion depends to a large extent on fuel–air mixing. More complete combustion results in a higher cylinder pressure than incomplete combustion.[13,14] Diesel exhibited a slightly lower peak cylinder pressure than Jatropha A; this finding could be a result of oxygen–fuel mixing, which is more efficient in fuel that contains intrinsic oxygen.[16,25]

Heat release

Figure 9 depicts peak heat release rates for the different fuels. Figure 10 illustrates the variations of heat release with crank angle degree for the fuels at full load conditions and a constant engine speed of 3000 rpm. Similar trends were observed at other loads and differed only in the magnitude of heat release and the corresponding crank angle at which the heat release occurred. For all fuels, the peak heat release increased as the load increased, possibly as a result of high temperature and high cylinder pressure, better fuel–air mixing, and higher flame velocity at higher loads. All fuels experienced rapid pre-mixed burning followed by diffusion combustion, as is typical for naturally aspirated engines. After the ignition delay period, the pre-mixed fuel–air mixture burns rapidly, releasing heat at a very rapid rate, after which diffusion combustion takes place, during which the burning rate is controlled by the availability of the combustible fuel–air mixture. It can be seen that Jatropha A and B showed an improvement in the heat release rate during the pre-mixed combustion period. The presence of oxygen in these fuels decreased their cetane number and increased the ignition delay period. Therefore, while the engine was running with biodiesel, increased accumulation of fuel during the relatively longer delay period resulted in a higher rate of heat release. Even though diesel exhibited a higher heating value and lower viscosity, the intrinsic oxygen property of the other fuels influenced the heat release results obtained. Because of the shorter delay period for diesel, its maximum heat release rate occurred earlier in comparison with the jatropha fuels. Jatropha A's higher heat release compared with Jatropha B is probably because of its higher heating value and lower viscosity.

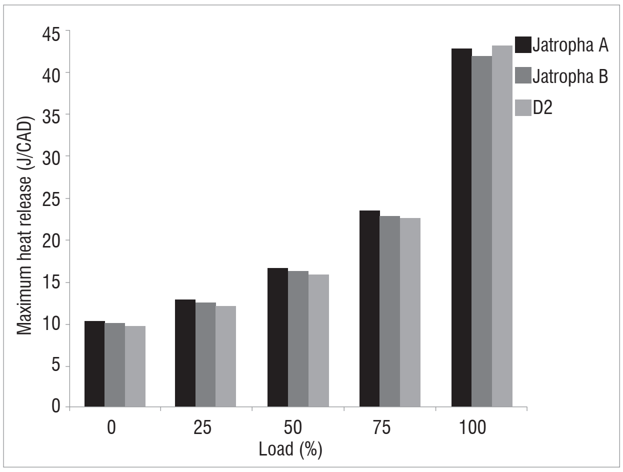

Figure 9: Maximum rate of heat release at different engine loads.

Effect of geographical location on jatropha oil properties

A good explanation of why different regions produce jatropha oils with different properties was given by Zhang et al.[26] While studying the genetics of the plant, they discovered that the plant tends to adapt to its specific habitat at a specific altitude and latitude, and changes its characteristics in the process. They further explained that these geographical environments have different ecological factors that result in the exposure of the plants to different selection pressures, eventually leading to genetic differentiation among plants from different regions. The same observations were made by Kaushik et al.[27] in their genetic study of the seed traits and oil content of *Jatropha* from different locations in India. Kaushik et al. explained that the variations in jatropha seeds with respect to their morphological characteristics could be because the species grows over a wide range of rainfall conditions, temperatures and soil types. Ovando-Medina et al.[28] also concluded that *Jatropha* trees differ according to their geographical origin. Their study, which was conducted on trees from different regions in Mexico, indicated a correlation between chemical properties and geographical location. Similar observations were made by Popluechai et al.[29] who reported that jatropha oil from different parts of the world (Africa, Asia and South America) exhibited different genetic and physicochemical characteristics. Thus, different regions with different geographical and environmental conditions produce trees with different characteristics.

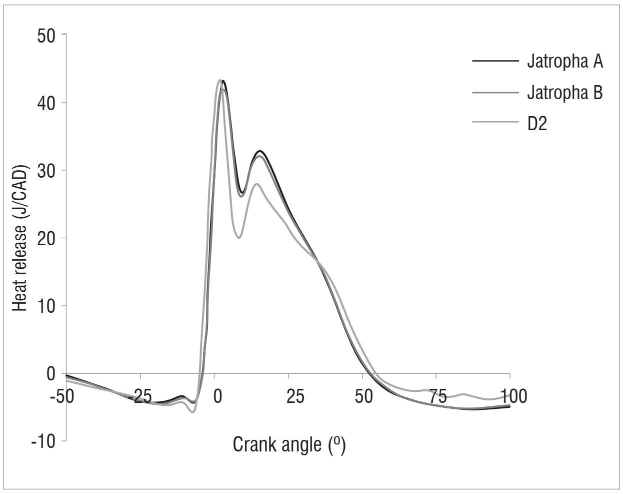

Figure 10: Heat release variation with crank angle at full load.

Conclusion and recommendations

A two-step acid–alkaline catalytic transesterification process was used to prepare two samples of jatropha oil from different countries in East Africa. The samples produced were compared with each other and to fossil diesel in terms of engine emissions and combustion characteristics. It was observed that the biodiesels had different emission and combustion characteristics, although both performed better than the fossil fuel. It was not clear which biodiesel performed best overall because Jatropha A was better in some cases and Jatropha B in others. The difference between the biodiesels is related to the respective geographical locations of the original oils. Different geographical locations produce plants with varying characteristics as a result of the different ecological and environmental conditions to which the plants genetically adapt.

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